

Integrated Navigation Sensor Platform for EVA Control and Testing (INSPECT) for SPHERES

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Executive Summary (GK, MK)

The NASA Human Exploration and Operations Mission Directorate (HEOMD) is invested in researching technologies that could reduce risks associated with astronaut spacewalks. One of these technologies envisioned by the directorate is an autonomous system capable of inspecting the exterior of space hardware, a common reason for sending an astronaut outside of the International Space Station (ISS). The INSPECT system, an Integrated Navigation Sensor Platform for Extravehicular Control and Testing, has been developed as a first step in the progression towards developing a system capable of operating outside of the ISS and serving the HEOMD's needs. The sensors on INSPECT were selected to fulfill the mission-level requirements to reduce risk by testing capability inside of the ISS prior to moving into the vacuum of space.

The INSPECT system is an addition to an existing microsatellite system known as SPHERES, Synchronized Position Hold Engages Reorient Experimental Satellites, built by the MIT Space Systems Laboratory. These satellites have been tested aboard the ISS and were originally created to serve as a testbed for control algorithms. The core of INSPECT is Halo, a structure mounted onto SPHERES that provides six ports for attaching additional sensors and actuators. The sensors and actuators of INSPECT include VERTIGO (Visual Estimation for Relative Tracking and Inspection of Generic Objects), an already-designed and tested system for SPHERES that provides computing power and visual capability for INSPECT; two pairs of Control Moment Gyroscopes (CMGs) that allow for attitude control; an Optical Rangefinder (ORF) that provides depth perception mapping; and a Thermographic Camera that produces a 2D thermal map. These components comprise of five ports of the Halo, and the sixth port face of the Halo structure will be dedicated to a Universal Docking Port (UDP).

The overall integrated system (SPHERES, Halo, and INSPECT suite) mass is 17.43 kg, with the INSPECT suite components accounting for 8.08 kg of that total. With an anticipated average and peak power draw of 22.31 and 40.98 W, the team has designed Printed Circuit Boards (PCBs) for the ORF, ThermoCam, and CMGs to interface with their respective Halo ports. The Optical Rangefinder for the INSPECT prototype is the Mesa SR4000, selected for its 69° by 56° field of view and ability to meet INSPECT accuracy and precision requirements. The Thermographic Camera is a FLIR A5 with a 44° by 36° field of view and the ability to detect temperature differences of less than 1° . The CMGs on INSPECT are Honeybee's Low Earth Orbit Control Moment Gyroscopes, providing attitude control for navigational maneuvers.

The INSPECT team is composed of two principal investigators, a project manager, systems lead, chief engineer, and the following subsystems: Systems, Structures, ThermoCam, ORF, CMGs, and VERTIGO. The INSPECT Hardware Acceptance Review was conducted on April 18, 2014 and a preliminary prototype was demonstrated and delivered at the INSPECT Bench Review on May 13, 2014.

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List of Acronyms

Acronym	Meaning
ADCS	Attitude Determination and Control System
CMG	Control Moment Gyroscope
CPU	Central Processing Unit
CBE	Current Best Estimate
DSP	Digital Signal Processor
FPS	Frames Per Second
GPF	Goggles Program File
HEOMD	Human Exploration and Operations Mission Directorate
HP	Halo Port
HPG	Halo Port (Goggles)
IMU	Inertial Measurement Unit
INSPECT	Integrated Navigation Sensor Platform for EVA Control and Testing
ISS	International Space Station
LIDAR	Light Detection and Ranging
MIT	Massachusetts Institute of Technology
MIC	Multiple Interface Connection
NASA	National Aeronautics and Space Administration
NETD	Noise Equivalent Temperature Difference
ORF	Optical Rangefinder
PCB	Printed Circuit Board
PoE	Power over Ethernet
PPTC	Polymeric Positive Temperature Coefficient Device
ROS	Robot Operating System
RTD	Resistance Temperature Detector
SLAM	Simultaneous Localization and Mapping
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellites
SSL	Space Systems Laboratory
ToF	Time-of-Flight
TORC	Tiny Operationally-Responsive CMGs
UDP	Universal Docking Port
VERTIGO	Visual Estimation for Relative Tracking and Inspection of Generic Objects

1 Introduction

1.1 Mission Statement (MC, MK)

The mission of INSPECT is to prototype and test a sensor/actuator suite as the first step to addressing NASA Human Exploration and Operations Mission Directorate (HEOMD) mission need for free-flying autonomous systems for extravehicular inspection and characterization.

1.2 Motivation and Vision (MC, MK)

As more technology is developed for in-space applications, NASA HEOMD envisions retrievable free-flying research platforms for the ISS and other host vehicles where scientific and technical research is conducted in a stand-off location (a location in free space approximately 5 km away from the host vehicle), or around the host vehicle itself.

Conducting research in a stand-off location is advantageous because of “less vibration and contamination, [ability to] support large deployable structures, [ability to] test relative sensing over long distances, [ability to] exercise rendezvous and circumnavigation, or [ability to] observe the host carrier from that stand-off position [1].” Thus, there is an incentive to construct free-flying autonomous systems that operate at these stand-off locations independent of the host vehicle. Multiple free-flyers could be used for providing multiple viewpoints for inspection and platforms for additional research.

Free-flyer autonomous systems can also be used for extravehicular inspection, navigation, and characterization around a host vehicle, which would reduce the need for risky astronaut extravehicular activities (EVAs). For example, on the International Space Station (ISS), the location, flow rate, and other details of an ammonia leak (whether inside a pump package itself or from a defect in a truss structure segment) could be more precisely determined before astronauts perform an EVA, rather than relying on imprecise visual methods from inside the ISS. Additional benefits include detection of electrical faults, insulation deterioration, and general monitoring of health and wellness of vehicle components [1]. Thus, the development of free-flying autonomous systems has potential to aid astronauts and reduce exposure to unidentified issues.

The MIT Space Systems Lab (SSL) Synchronized Position, Hold, Engage, Reorient, Experimental Satellites (SPHERES) [2] (Figure 1), are eligible candidates for use as the base design for these free-flying autonomous systems. However, modification is required for the SPHERES microsatellites to be able to address NASA HEOMD’s mission. For example, they must be radiation-hardened and designed to withstand the harsh space environment, and the appropriate hardware, instrumentation, software, and sensors need to be added to perform inspection, navigation, and characterization. With help from technologies from the MIT Space Systems Laboratory and Draper Laboratories (such as the Halo structure and CMGs), the INSPECT system is the first step towards creating microsatellites that realize NASA HEMOD’s vision.



Figure 1: SPHERES operating inside ISS (left); SPHERES microsatellite (middle); concept of free-flying autonomous systems (derived from SPHERES architecture) near ISS (right) [25]

1.3 Team Organization (MC, JB)

Figure 2 outlines the organization and contributors of the INSPECT design team. Contact information for all team members may be found in

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Appendix A: Contact Information.

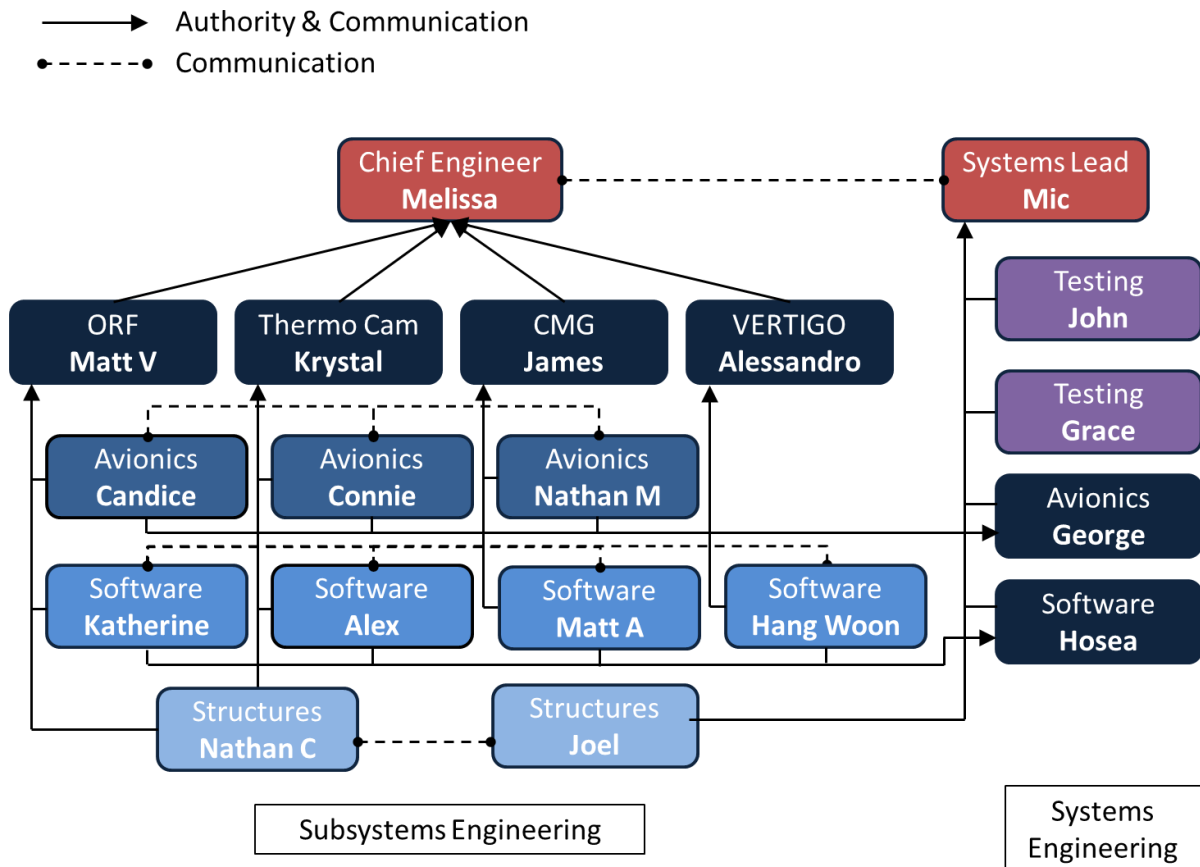


Figure 2: Team Organization Structure (JB)

2 Mission Overview

2.1 Context (JW)

INSPECT 16.83x is the first of four steps towards satisfying NASA HEOMD's goal of a free-flying autonomous systems for extravehicular inspection and characterization.



Figure 3: HEOMD Mission Flow

Step 1: INSPECT 16.83x is meant to provide a working test platform for ground testing that can later be developed into a prototype to be flown on the International Space Station.

Step 2: INSPECT on the ISS is meant to be a fully functioning inspection probe to be used inside the International Space Station that can be matured into a design that can be used for ISS EVA testing.

Step 3: SPHERES-X is the name temporarily assigned to the future inspection probe that is capable of working in the space environment. It is to be fully integrated with the International Space Station.

Step 4: The final HEOMD Mission is to be of the same capabilities of SPHERES-X, but with the ability to be integrated with a number of space vehicles.

2.2 INSPECT Mission and Systems Requirements (JW, JB, MC)

ID	Name	Requirement	Parent	Rationale	Verification Method
Mission Statement					
MS-1	INSPECT Mission	The mission of INSPECT is to prototype and test a sensor/actuator suite to facilitate NASA Human Exploration and Operations Mission Directorate (HEOMD) mission need for free-flying autonomous systems for extravehicular inspection and characterization.			
Mission Level Requirements					
M-1	Prototype	The INSPECT sensor/actuator suite shall be designed as a prototype payload for SPHERES to test specific operational modes inside the ISS.	MS-1	These operational modes correspond to potential extravehicular functions for systems such as SPHERES-X.	Analysis
M-2	Risk Reduction	INSPECT shall reduce risks associated with the new sensor/actuator system by using SPHERES testing capability inside the ISS.	MS-1	Opportunity for design iteration prior to moving outside of the ISS	Analysis
ISS Requirements					
ISS-1	Test Space Limitations	The system shall remain inside a predetermined operational volume of the JEM (4.2 m diameter, 11.2 m length) for inside-ISS operations.	M-2	Remove risk of entering a region of space from which the system cannot be recovered, and to stay within range of the communication system.	Inspection
Verification		<i>Verified:</i> CONOPS designed to perform all maneuvers in JEM volume			
ISS-2	ISS Storage Size	The suite shall be able to fit into a full-size Crew Transfer Bag (CTB) (42.5 cm by 50 cm by 25 cm)	M-2	Need for storage on ISS in TBD storage configuration	Inspection
Verification		<i>Verified:</i> Initial inspection confirms system must be broken down and mounts removed to fit in Crew Transfer Bag.			
ISS-3	Package Launch	The system packaging shall be compliant with Progress/Soyuz safety document P32928-103 and SSP 50146, Attachment D	M-2	Launch vehicle requirement; http://kscsma.ksc.nasa.gov/GSRP/Document/ssp30599D.pdf	Analysis
Verification		<i>Unverified:</i> No system packaging has been designed or manufactured, and is scheduled for Summer 2014			
ISS-4	Airlock Size	The fully integrated system shall be capable of fitting in the 57.6 x 83 x 80 cm JEM airlock.	M-2	Need to fit through airlock to accommodate future capabilities/mission	Inspection

				outside ISS	
Verification		Verified: CAD models indicate entire system cubic volume of 0.0363357m ³ using square mockups for different subassemblies: SPHERES + Halo, ORF, Thermo, CMGs, VERTIGO stack, and VERTIGO goggles.			
System Requirements					
S-1	Downlink	The system shall allow for stored information to be transferred to a host computer	M-1	Allows for transfer of data from avionics stack to another processing device for data analysis	Inspection
Verification		Verified: VERTIGO Avionics Stack supports data offload via USB using designated dongle directly connected between host computer and avionics stack			
S-2	Mass Limit	The system shall not exceed 11 kg in mass.	M-1	Excessive inertia will limit the flight time because more fuel will be required for control and movement.	Analysis
Verification		On-track: Total mass currently 8.079kg			
S-3	Power Limit	The system shall not exceed a peak power draw of 16.65 watts at each port. (11.1V and 1.5 amps)	M-1	Excessive power draw will present health risks to avionics, decreasing mission lifespan.	Testing
Verification		Verified: ORF requires greatest power draw of 13.36W			
S-4	SPHERES	The system shall use SPHERES as the primary testbed for all operations	M-2, M-1	SPHERES provides a consistent testbed that has ISS heritage	Inspection
Verification		Verified: All systems designed to interface with SPHERES			
Halo Requirements					
H-1	Physical Connection	Each suite component shall connect to Halo using the 4-hole square screw pattern	S-4	Assures consistent mounting	Analysis
Verification		Verified: All sensors and actuators connect via mounts			
H-2	Data Connection	Each suite component shall be able to connect to the Halo via USB 2.0 or Ethernet	S-4	SPHERES will be utilized as the foundation for the sensor/actuator suite	Analysis
Verification		Verified: All subsystems have been successfully connected to a Halo using USB 2.0 or Ethernet via HPG			
H-3	Power	Each suite component shall operate with no more than 16.65W and be able to convert operational current/voltage from 11.1V/1.5A	S-4	Each Halo port provides 11.1V at a maximum of 1.5A before tripping a breaker	Analysis
Verification		Verified: All subsystems have interface boards to convert voltage and operate within power limit			
H-4	Force Limit	The suite shall not impose a force greater than 40 N in the Z direction to SPHERES	S-4	Friction mount is not meant to operate above this force	Analysis
Verification		Verified: Analysis shows 79N force in Z direction, which was compensated for by adding supports to the testing structure to support Halo, decreasing total force on Halo to less than 10N			
SPHERES-X Traceable Requirements					
SX-	Navigation	INSPECT shall provide a	M-1	Needed to fulfill	Analysis

1		functional API for localization and mapping.		mission goal properly test the system	
Verification		Verified: Software data alignment successful and data output in format compatible with standard autonomous SLAM protocols			
SX-2	Inspection	INSPECT shall provide a functional API for identification and description of observable objects.	M-1	Needed to fulfill mission goal and properly test the system	Analysis
Verification		Verified: Software data alignment successful and data output in format compatible with standard autonomous identification protocols as well as human visible identification			
SX-3	Health Monitoring	INSPECT shall provide a means of assessing functionality of its components as a form of health monitoring	M-1	System must assess when it can no longer perform its mission safely	Analysis
Verification		Unverified: Printed Circuit Boards designed and not tested successfully for health-monitoring properties			
SX-4	Algorithms	INSPECT shall provide a functional API for the testing of future software.	M-1	System needs to test software for future missions	Analysis
Verification		Verified: Software saved to Sata drives 10 and 11 with support for future software			
SX-5	Navigation Platform	INSPECT shall provide a platform for navigational algorithm development.	M-1	Guest scientists will program navigation paths, INSPECT must support this	Analysis
Verification		Verified: Software data alignment successful and data output in format compatible with standard autonomous navigation protocols			
INSPECT Suite Requirements					
I-1	ISS Operation Time	The system shall be capable of operating for no fewer than 30 minutes without refueling or recharging.	M-1	Needs to limit the amount of fuel and power used by INSPECT so that future EVA operations are a reasonable amount of time	Analysis
Verification		Unverified: All three forward-facing sensors and the avionics stack operate for 30 minutes, but CMGs have not been tested using power from Halo. Testing scheduled for Summer 2014			
I-2	Life Span	The suite shall be capable of performing 250 test cycles over its operational life.	M-1	Needs to last for a significant amount of time on station in order to evaluate the possibility of SPHERES-X	Analysis
Verification		Unverified: Only 20 test cycles completed as of 14May2014			
I-3	Flat Floor Operation Time	Each system Concept of Operations mode shall be completed using no more than one full set of fuel tanks.	M-1	Each mode being tested on the flat floor must be completed without being interrupted for refueling	Testing
Verification		Verified: Total fuel consumed: 29% of two-tanks combined			
I-4	SPHERES compartment	The suite shall not interfere with battery or fuel compartments	S-4	Maintain SPHERES operations	Inspection

Verification		<i>Verified:</i> CAD model confirmation and visual inspection			
I-5	SPHERES actuators	The suite shall not interfere with SPHERES thrusters or sensors	S-4	Maintain SPHERES operations	Analysis
Verification		<i>Unverified:</i> Final CMG wiring positions being designed to be implemented Summer 2014			
I-6	SSL Testing	The system shall be able to be tested in the SSL	M-2	Allows for ground testing	Analysis
Verification		<i>Verified:</i> All testing has been successfully conducted and planned for the SSL			
I-7	Software Update	The system shall be able to update its software	SX-4	Allows for testing of new algorithms	Analysis
Verification		<i>Verified:</i> The use of GPFs on VERTIGO and GSP on SPHERES insures inherent updatability of software.			
I-8	Sensor Placement	The sensors shall point in the same direction and be placed no more than 50cm apart.	SX-1, SX-2	Allows for combined field of view for sensors	Inspection
Verification		<i>Verified:</i> CAD models and machined mounts designed and inspected to confirm			
I-9	Computing Power	INSPECT shall provide a minimum of 300Mflops of computing power at all times to support the execution of guest scientist algorithms.	SX-4, SX-5	Need to ensure sufficient resources to run code so system doesn't crash	Testing
Verification		<i>Unverified:</i> Current estimates are positive, but confirmation testing scheduled to take place Summer 2014			
System Safety Requirements					
SAF-1	Linear Momentum	The system shall not exceed a linear momentum of 1 kg-m/s.	ISS-5	Prevents hazard if control is lost	Testing
Verification		<i>Verified:</i> CONOPS testing conducted on SSL Flat Floor confirms max linear momentum of 1.038 kg-m/s, which is less than what will be on ISS given the additional weight of the air carriage			
SAF-2	Mounting	The suite shall not be structurally mounted during transportation.	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> In order to fulfill ISS-2, this requirement is also met			
SAF-3	Hazardous substance	The suite shall not contain any substance that would cause a hazard if released	ISS-5	ISS Safety Requirement	Analysis
Verification		<i>Verified:</i> No hazardous substances detected			
SAF-4	Depressurization	The suite shall not create a hazard in the event of depressurization or re-pressurization of the surrounding volume	ISS-5	ISS Safety Requirement	Analysis
Verification		<i>Unverified:</i> No pressurization testing planned for SP14			
SAF-5	Pressure vessel	The suite shall not contain any components under pressure	ISS-5	ISS Safety Requirement	Analysis
Verification		<i>Verified:</i> No component specs require pressurization and all tests indicate no concern			
SAF-6	Ignition sources	The suite shall not contain any active ignition sources or self-igniting materials	ISS-5	ISS Safety Requirement	Analysis

Verification		<i>Verified:</i> All currently manufactured components meet requirement			
SAF-7	Ionization	The suite shall not contain any sources of ionizing or non-ionizing radiation	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> Acceptance testing indicates no concern of ionization			
SAF-8	Lasers	If the suite contains a laser it shall meet ANZI Z136.1-2000 for Class 1, 2, or 3a lasers (power measured at the source) or SSP 50094	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> ORF light source is a Class 1 laser and meets specified requirements			
SAF-9	Protective Covers	The suite shall provide covers for mechanical parts which pose a danger if touched, but may not provide shatter resistance	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> CMG Enclosures manufactured and inspected to confirm			
SAF-10	Cleanliness	The suite's surface and packaging shall be disinfected prior to launch	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Unverified:</i> System has ability to be easily cleaned, but no packaging has been designed or manufactured. This is scheduled for Summer 2014			
SAF-11	Harmful substances	The suite shall not contain any biological substances, toxic substances, or alcohol	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> No known harmful substances are present on the system			
SAF-12	Pyrotechnics	The suite shall not contain pyrotechnics	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> No component contains pyrotechnics			
SAF-13	Cryogenics	The suite shall not contain any cryogenics	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> No component contains cryogenics			
SAF-14	Appendage Entrapment	The suite shall not contain any hardware that create a potential appendage entrapment	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> All components designed for flush connections to prevent appendage entrapment			
SAF-15	Sharp Edges	The suite shall not contain any sharp edges	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> All components verified to have no sharp edges to touch			
SAF-16	Pinch Points	The suite shall not contain any hardware that could create a pinch point	ISS-5	ISS Safety Requirement	Inspection
Verification		<i>Verified:</i> All components verified to have no pinch points or are enclosed to avoid pinch points			
Sensing Requirements					
SEN-1	Field of View	All imaging sensors shall have a minimum field of view of 33 degrees by 33 degrees.	SX-1, SX-2	Expectation of 30 degree rotation per image sequence with 10% overlap	Testing
Verification		<i>Verified:</i> All sensors meet requirement, limiting sensor: ThermoCam with 44 x 36 degrees			
SEN-2	Target	The system shall determine	SX-1,	Defines ranging limits	Testing

	Distance	the distance to a target object accurate to within 10 cm with precision to 2 cm up to 10 meters away	SX-2		
Verification		Verified: ORF and VERTIGO independently meet requirement			
SEN-3	Visible Light Image	The system shall resolve a visible-light image of a 1cm per pixel resolution from 1 m	SX-1, SX-2	Defines optical resolution limits.	Testing
Verification		Verified: VERTIGO has 4 pixels per 1cm x 1cm square at 1m from target			
SEN-4	Sensor Data	All sensors shall send data at a rate which can be processed by the VERTIGO computer or must include its own computer for data processing	SX-4	Need to transfer data	Testing
Verification		Verified: All sensors operate simultaneously and are limited by bandwidth of network before VERTIGO			
SEN-5	Thermal Image	The system shall resolve a thermal image of a 5x5 cm object from a distance of 1 m to +/- 5 degrees C accuracy and a noise equivalence temperature difference of <1 degree C at 20 degrees C.	SX-1, SX-2	Defines thermal resolution limits and accuracy/precision to produce a reasonable thermal image for our purposes.	Testing
Verification		Verified: ThermoCam meets requirement within +/- 2.5 degrees C			
SEN-6	Pose Sensors	The system shall be able to determine its pose in 2 dimensional space with 1 axis of rotation normal to the test floor	SX-1, SX-2, SX-5	Ability to support guest scientist navigation algorithms necessitates navigational sensors	Testing
Verification		Verified: The design choice to use SPHERES as a platform inherently meets this requirement			
Control Requirements					
C-1	Sensor Stabilization	The system shall stabilize all sensors to have a blur coefficient of less than or equal to 1. Blur coefficient = $(t_{int}/\theta_{res})\omega$	SEN-1	Sensors must be sufficiently isolated from vibration in order to prevent blurring of image data	Testing
Verification		Verified: ThermoCam has maximum blur coefficient at 0.16			
C-2	Translation	System shall be able to translate in a controlled manner through three dimensional space in a microgravity environment to 1 cm accuracy.	SX-1, SX-2	Translation is necessary for navigation.	Testing
Verification		Verified: The design choice to use SPHERES as a platform inherently meets this requirement, confirmed by ConOps testing			
C-3	Attitude	System shall be able to control its attitude through three dimensional space in a microgravity environment to 0.5 degree accuracy.	SX-1, SX-2	Attitude control is necessary for navigation.	Testing

Verification		<i>Unverified:</i> RGA testing scheduled for Summer 2014			
C-4	Angular Velocity	System shall be capable of achieving an angular velocity below 0.58 rpm (in inspection mode) and below 9 rpm (in navigation mode).	SX-1, SX-2	Sensor blur requirements during inspection and SPHERES internal gyroscopes during navigation limit allowable angular velocity	Testing
Verification		<i>Verified:</i> Flat Floor testing confirms precise rotation rates anywhere in the range below 9 rpm			
C-5	Saturation	The system shall be able to track saturation levels at all times.	SX-1	Need to know when CMGs are approaching saturation to maintain command authority	Testing
Verification		<i>Verified:</i> Testing confirmed and recorded saturation levels			
Actuation Requirements					
A-1	Sensor Movement	The actuators shall provide movement for sensors that require motor functions.	C-1	Some sensors may require increased field of measurement.	Inspection
Verification		<i>Verified:</i> No sensors require motor functions			
A-2	Torque	The system shall be capable of producing a torque of at least 11x10-3 Nm.	C-4	Based on SPHERES torque capability	Testing and Analysis
Verification		<i>Verified:</i> Testing and analysis confirms 0.34Nm total max torque, well above requirement			
A-3	Linear Acceleration	The system shall be capable of linearly accelerating at 0.02 m/s^2	C-3	Allows for system translation	Testing
Verification		<i>Verified:</i> Fully-laden mock system test verify requirement			

2.3 Concept of Operations

2.3.1 Operating Environment (JW, GK)

The laboratory testing floor consists of a 5 m x 5 m octagonal epoxy surface. The SPHERES-INSPECT system can be mounted to air carriages, which float on the glass surface by means of compressed gas. This arrangement allows planar translation and single-axis rotation about the y-axis. INSPECT nominal operations will consist of a 2 meter long landscape to be imaged from a distance of 1 meter away.

Adjacent to the testing surface will be a test landscape meant to simulate depth, thermal, and visual stimuli. This testing landscape will allow for complete requirement testing as well as future research and development of the INSPECT platform.

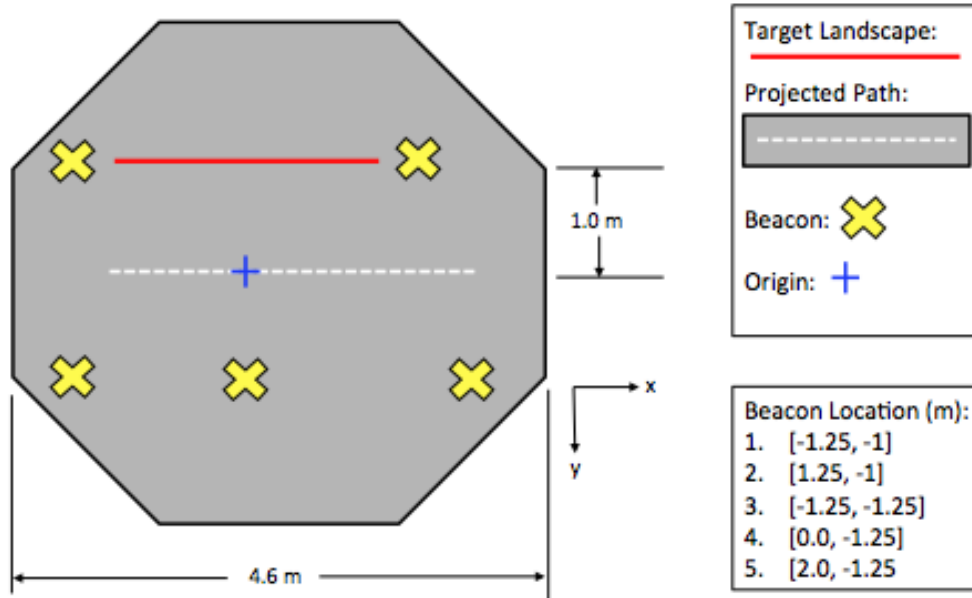


Figure 4: Layout of the Testing System

2.3.1.1 Inspection Landscape

A quasi-2D 200cm x 61 cm test board has been designed to quantitatively judge an inspection operation.

An effort was made to create a landscape that displays each stimulus at a range of resolutions:

1. A specification more stringent than the requirement
2. At the requirement
3. A specification much easier to achieve than the requirement.

The ability to inspect a broad spectrum of stimuli will allow for complete requirement testing and gives flexibility for future inspection studies.

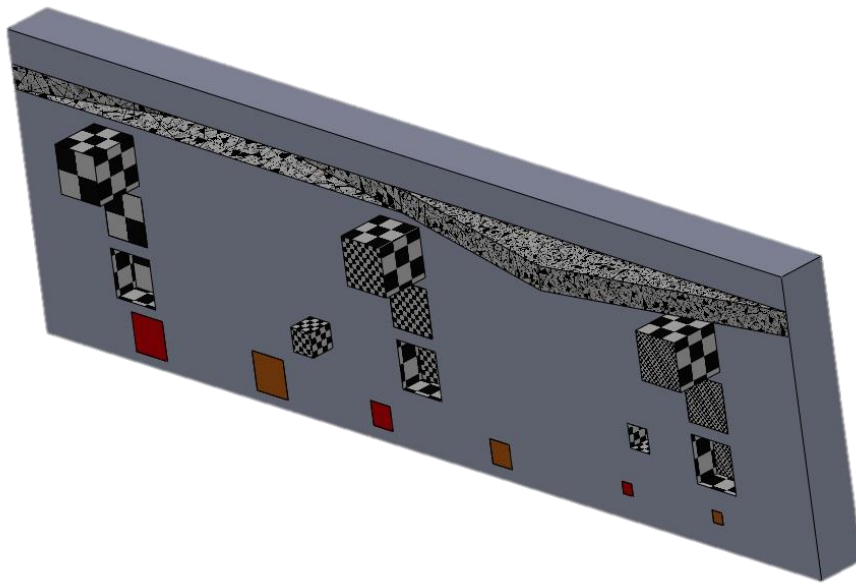


Figure 5: The Inspection Landscape

2.3.1.1.1 Visual stimuli

A checkerboard pattern of various resolutions can be used to test the distance at which the grey scale visual camera can no longer differentiate visual light. The following resolutions have been chosen:

1. 0.5 cm x 0.5 cm: More stringent than requirement
2. 1 cm x 1 cm: At requirement
3. 5 cm x 5 cm: Less stringent than requirement

2.3.1.1.2 Depth Stimuli

A continuous sloping test section ranging from -10 cm to 10 cm in depth from the neutral depth of the board allows for precise range resolution from testing from any distance.

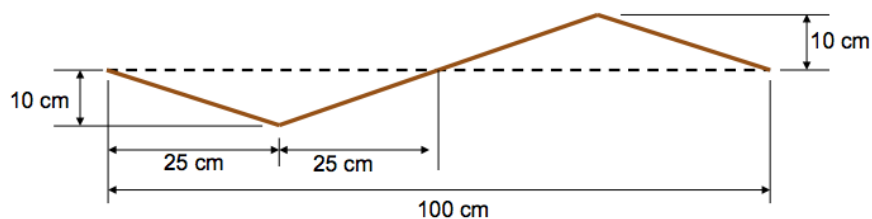


Figure 6: Continuous Change of Depth Stimulus

This continuous depth stimulus is covered in a unique pattern to allow for precision image overlapping.

For compounded stimuli depths of -5 cm, 0 cm, and 10 cm from the neutral plane of the board have been selected as discrete depths for stimuli. This allows for the following ranges of depth changes to be observed:

1. 0 cm to -5 cm, 5 cm depth change: More stringent than requirement
2. 0 cm to 10 cm, 10 cm depth change: At requirement
3. -5 cm to 10 cm, 15 cm depth change: Less stringent than requirement

2.3.1.1.3 Thermal Stimuli

Thermal resolution will need to be tested both in terms of amplitude of the stimuli and the size of the stimuli.

The heated areas will be of the following sizes:

1. 3x3 cm: More stringent than requirement
2. 5x5 cm: At requirement
3. 8x8 cm: Less stringent than the requirement

The amplitude of temperature difference shall be ambient lab temperature, ambient lab temperature +5°C, and ambient lab temperature +10°C. This gives the following temperature gradients:

1. 5°C: At requirement
2. 10°C: Less stringent than the requirement

Though no non-zero thermal gradients are less than the at-requirement level, the bounds of the stimuli are predicted to be much less discrete than the non-thermal stimuli. This will give an opportunity to detect smaller temperature gradients than those explicitly defined by the temperature controllers.

The eight thermal stimuli will be heated using 2 systems of four resistors in parallel. Dimmers will be used for more dynamic voltage control allowing for more precise heating. Figure 7 illustrates the design and Table 1 shows the required power output of each resistor along with the needed resistance for a 20 volt DC source.

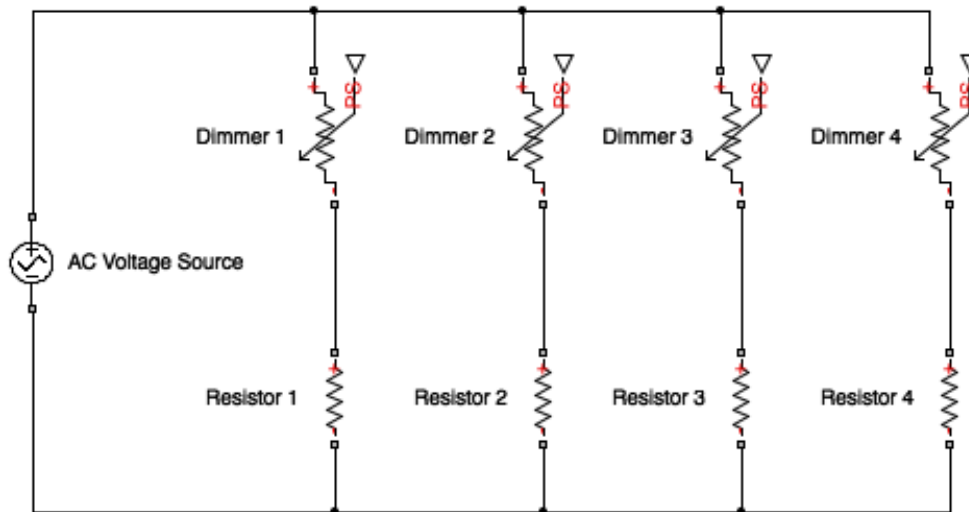


Figure 7: Heater Circuit Diagram

Note: Dimmers are represented by variable resistors in the diagram. Dimmers NOT variable resistors will be used for the real system. (JW, GK)

Table 1: Required Power and Resistors

	+5°C		+10°C	
	Voltage	Resistance (Ω)	Voltage	Resistance (Ω)
3x3cm	4.46	33	3.42	20
5x5cm	3.85	33	4.08	33
3x3cm	4.03	50	4.03	100

Each thermal stimuli is a manufactured aluminum plate that has the appropriate resistor attached to its back face. The front face of the plate is covered by black electrical tape to prevent thermal reflection caused by the reflective aluminum surface, allowing for a uniform temperature reading over the entire surface area of the plate. The plate is then inserted into its place within the test board and attached to its dimmer.

The test board used for integrated testing in May 2014 is displayed in Figure 8. (KAF)



Figure 8: INSPECT Test Board, May 2014

2.3.1.2 System Field of Views

The combined field of view created from individual sensor specifications as well as sensor placement is 33.55° (H) x 35.56° (V). From a distance of 1 meter this is equivalent to 59.53 cm (H) x 64.14 cm (V).

Limiting factors for horizontal field of view include both individual sensor field of view and sensor placement. The center of the horizontal field of view is located 14.37 cm from the center of the system.

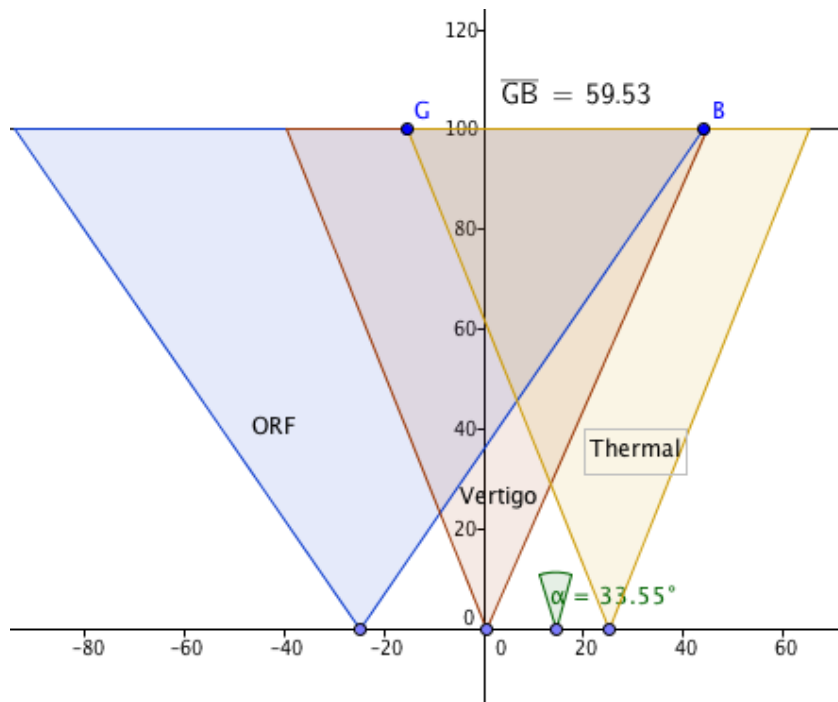


Figure 9: Horizontal Field of View

All sensors are located the on the same horizontal plane. This leads to only sensor field of view to be the limiting factor. The FLIR A5 has the smallest vertical field of view and thus is the limiting factor.

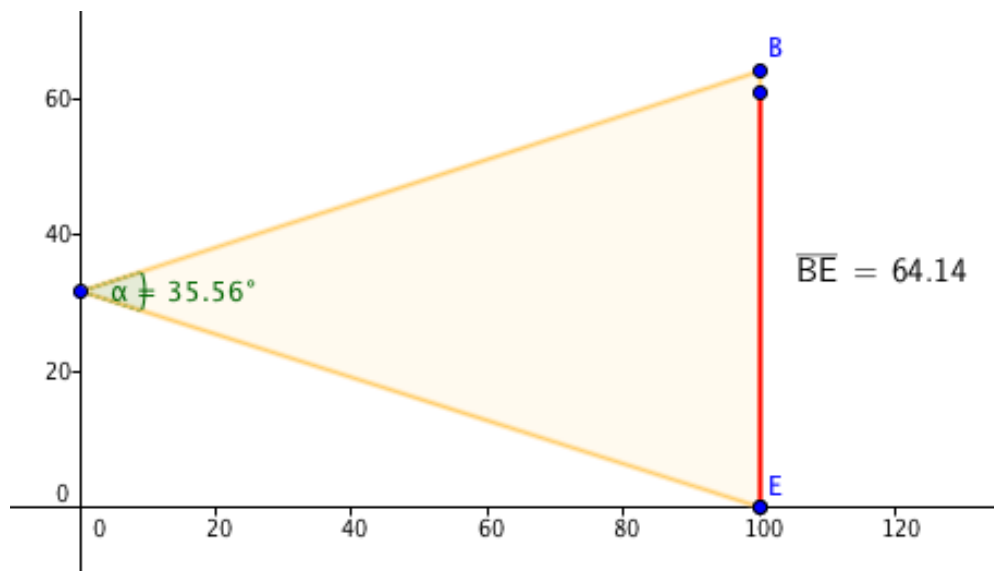


Figure 10: Vertical Field of View

2.3.2 Nominal Operations (JW)

2.3.2.1 Procedure Overview

The objective of INSPECT 16.83x missions is to simulate inspection maneuvers that will be traceable to testing missions aboard the International Space Station (ISS). The mission is split

into 5 steps to coordinate pre-maneuver, maneuver, and post-maneuver operations by INSPECT 16.83x.

Step 1: Pre-mission

During this phase, the operator will decide the target object that will be inspected by the system. He or she will also select and/or program one or more of the pre-defined inspection maneuvers.

Step 2: Assembly

During this phase, the components will be integrated with the SPHERES and Halo subsystems. Once all components are set up and turned on, the vehicle will be placed in the appropriate starting pose for the selected inspection maneuver.

Step 3: Inspection

During this phase, the system will execute the inspection maneuver chosen during the pre-mission stage

Step 4: Data Recovery

During this phase, data will be transferred from the VERTIGO avionics box to an off-system computer via a physical link.

Step 5: Disassembly

During this phase, INSPECT will be disassembled into its component subsystems and repackaged for storage.

2.3.2.2 Inspection Maneuver

The inspection maneuver carried out by the INSPECT system will consist of two phases. A pure translational inspection phase in which no non-attitude keeping attitude adjustments are necessary. The second phase is a pure rotational inspection phase in which no translational system movements are necessary. These maneuvers are optimal when the object of inspection is a landscape compared to one of a single object.

Basic Procedure

1. Characterize the length of the landscape being inspected
2. Determine the distance away from the target landscape at which inspection shall occur
3. Determine the locations along the path at which images shall be taken
4. Determine the accelerations needed to reach the locations at which images will be taken

The constraints put onto the trade study by our system are:

1. Sensor specifications
2. Blur requirements
3. Acceleration limits
4. System inertial and mass

The mass of our system is such that accelerating between images would be trivial to the overall speed of the system. Following this constraint the system shall accelerate to a drift velocity set forth by the blur requirement and maintains that speed until all images have been taken.

Figure 11 through Figure 18 show the inspection maneuvers necessary to carry out a complete inspection maneuver. Maneuvers 1-3 carry out the pure translational phase of the inspection. Maneuvers 4 and 5 transition system to the initial state for the pure rotational phase, and Maneuvers 6-8 carry out the pure rotational phase.

Maneuver 1: First image and linear acceleration to drift velocity

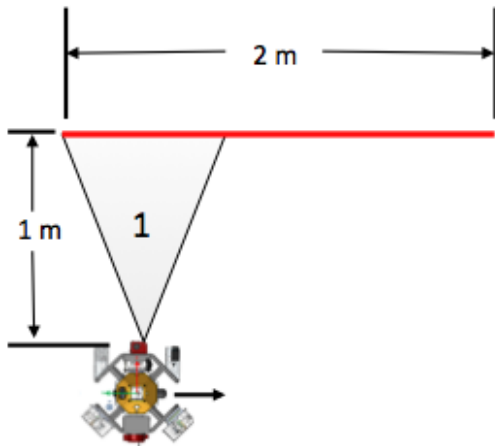


Figure 11: Maneuver 1

Maneuver 2: Translational imaging sequence

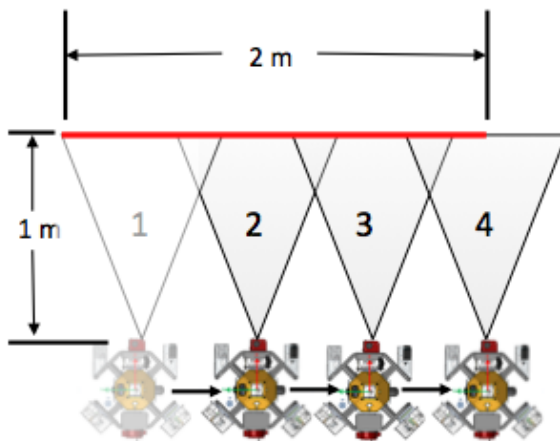


Figure 12: Maneuver 2

Maneuver 3: Linear deceleration

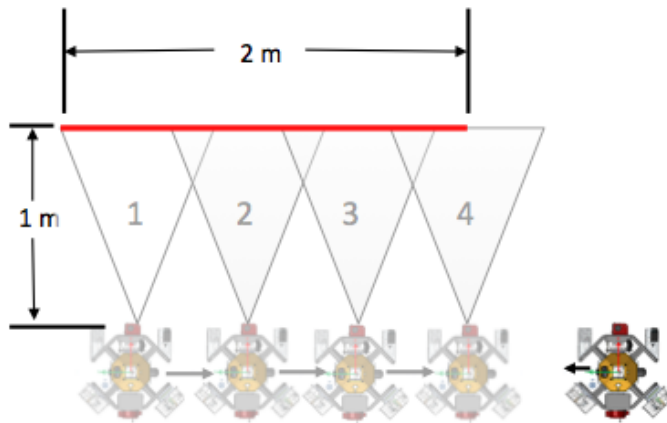


Figure 13: Maneuver 3

Maneuver 4: Rotation

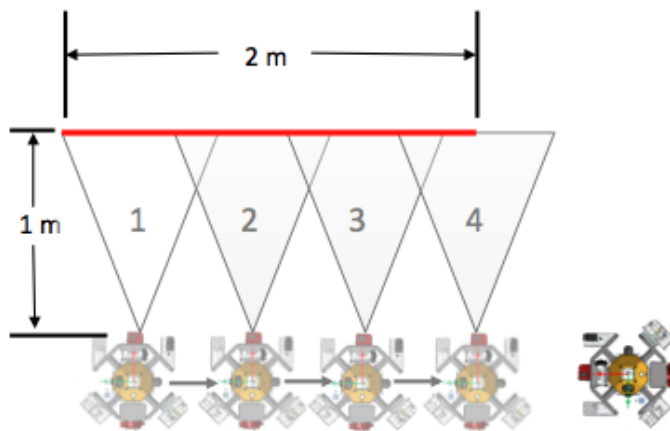


Figure 14: Maneuver 4

Maneuver 5: Translation to rotational inspection position

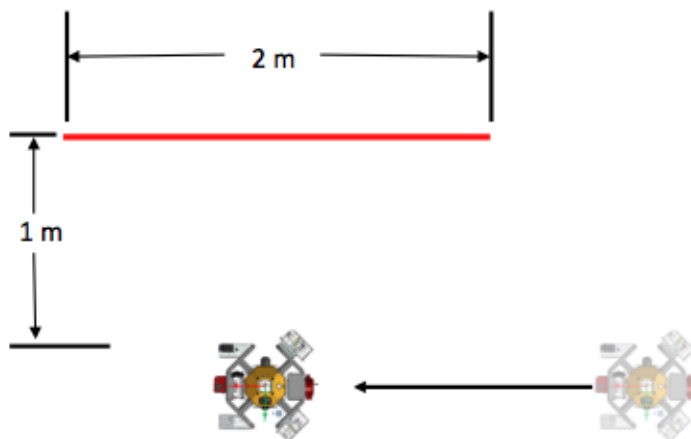


Figure 15: Maneuver 5

Maneuver 6: Acceleration to rotational drift velocity

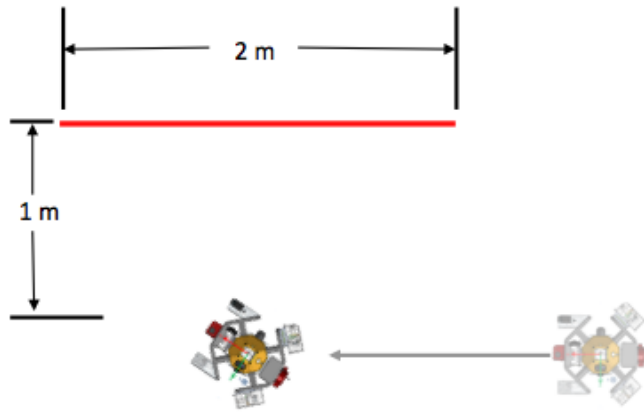


Figure 16: Maneuver 6

Maneuver 7: Rotational inspection imaging

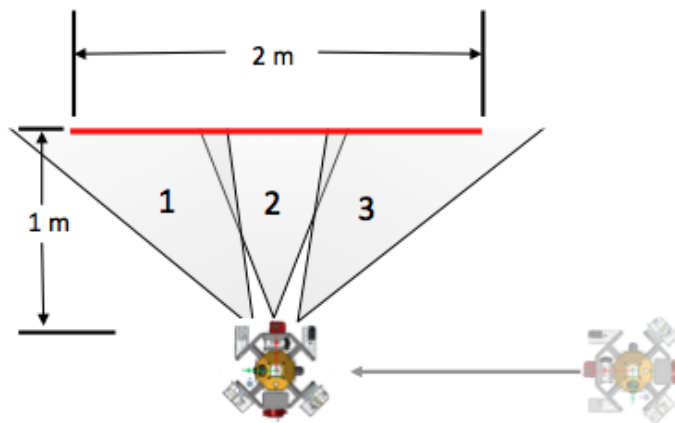


Figure 17: Maneuver 7

Maneuver 8: Rotational Deceleration

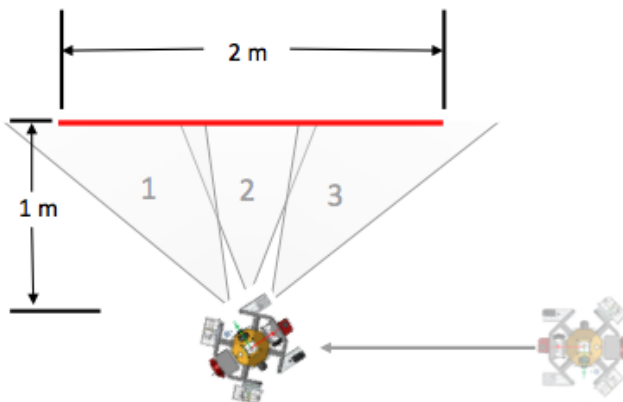


Figure 18: Maneuver 8

2.3.2.3 Inspection Maneuver Calculated Results

The complete inspection procedure has been modeled to allow for correct acceleration planning as well as the ability to compare real system functions to idealized maneuvers. The entire inspection maneuver shall consist of eight total images and take about 188.5 seconds to complete.

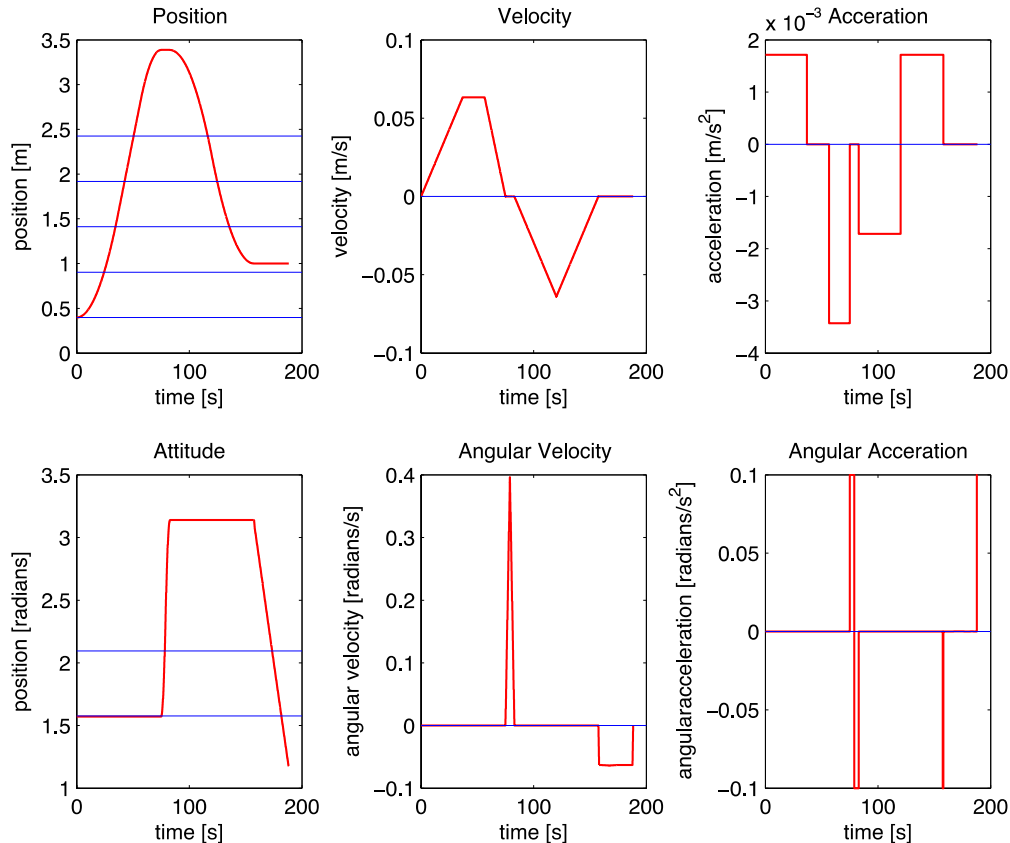


Figure 19: Modeled Inspections

2.3.3 Contingency Operations (JW)

Sensor Operation Termination:

Sensor termination will be implemented in situations where non-nominal current flow occurs for a given sensor. If excess current or no current is flowed to a sensor, all current to the sensor will stop.

Manual System Operations Termination:

Manual system termination can be implemented manually in situations where a component has encountered a malfunction that poses an immediate threat to other system components, test operators, or the testing environment.

2.4 Configuration Overview (MK, KAF)

As mentioned in 1.2 Motivation and Vision, the foundation for the INSPECT system is SPHERES, which provides a platform for testing control algorithms and physical maneuvers on the ISS.

SPHERES is represented in Figure 20 below. The right-handed SPHERES coordinate system is the same coordinate system to be utilized for the integrated INSPECT system, with the origin at the

geometric center of SPHERES (not including the SPHERES expansion port, used to connect an external component to SPHERES), the +X axis pointing out of the SPHERES expansion port, and the +Z axis pointing upward. The SPHERES shell, displayed in orange below, measures 21.3 cm x 21.3 cm x 21.3 cm.

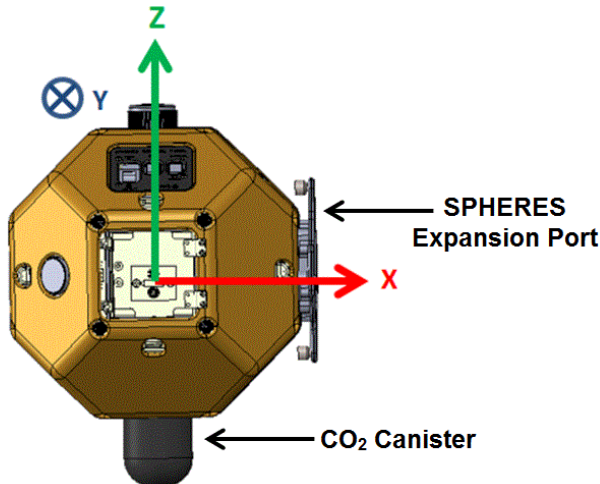


Figure 20: SPHERES Summary

With SPHERES as the main testing platform, INSPECT utilizes Halo, a structure being developed by the MIT Space Systems Lab in parallel with the INSPECT suite, in order to integrate multiple sensor components onto SPHERES. Halo, pictured in Figure 21 with SPHERES, interfaces with SPHERES and provides six functionally identical ports (with the exception of HPG, which is designed to be used with the VERTIGO Avionics Stack and Optics Mount) with mechanical and electrical interfaces that support USB 2.0 and Ethernet connectivity, allowing the addition of sensor components that can interact with SPHERES. A discussion of Halo in the context of INSPECT may be found in Section 4.1.1. (MK)

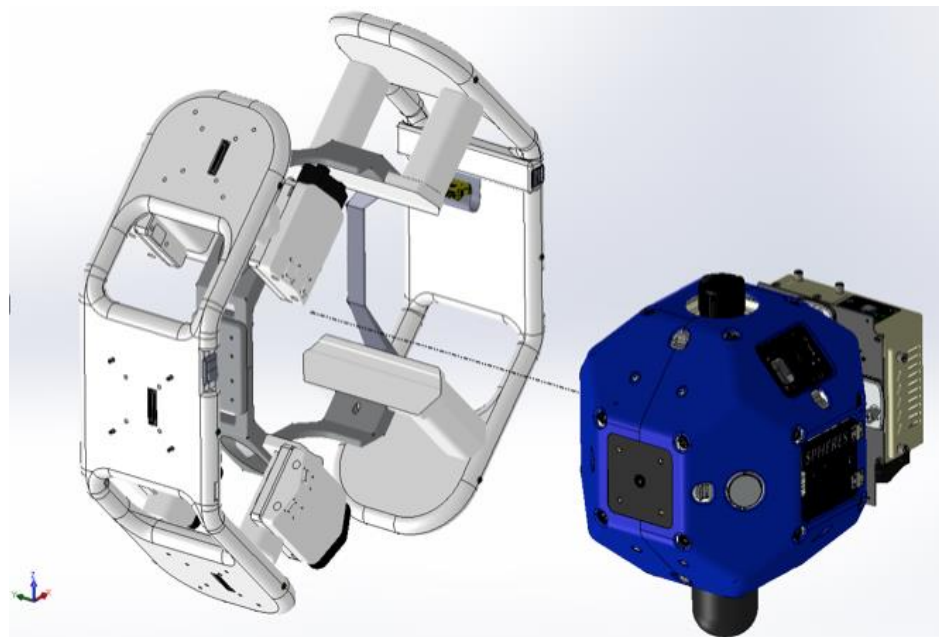


Figure 21: Halo Structure (Pictured with SPHERES and VERTIGO Avionics Stack) [3]

As of May 2014, the Halo prototype in existence is fully mechanically functional, allowing for all INSPECT sensors and actuators to successfully mount to their respective Halo ports. The prototype is not electrically functional, however, as the power and data lines running throughout the structure are not complete. Power is being successfully provided to all Halo ports except Halo Port #2 (see Figure 30), meaning that the INSPECT sensors and actuators could be powered through Halo as planned. Unfortunately, due to delays with the Control Moment Gyroscope (CMG) subsystem, the CMGs were not ready to interface for power with their designated Halo ports, causing integrated testing to be completed with the CMGs being externally powered via a wall outlet. The cable necessary for this modification is shown in Figure 22 (the single black cable leading off in the bottom of the figure).

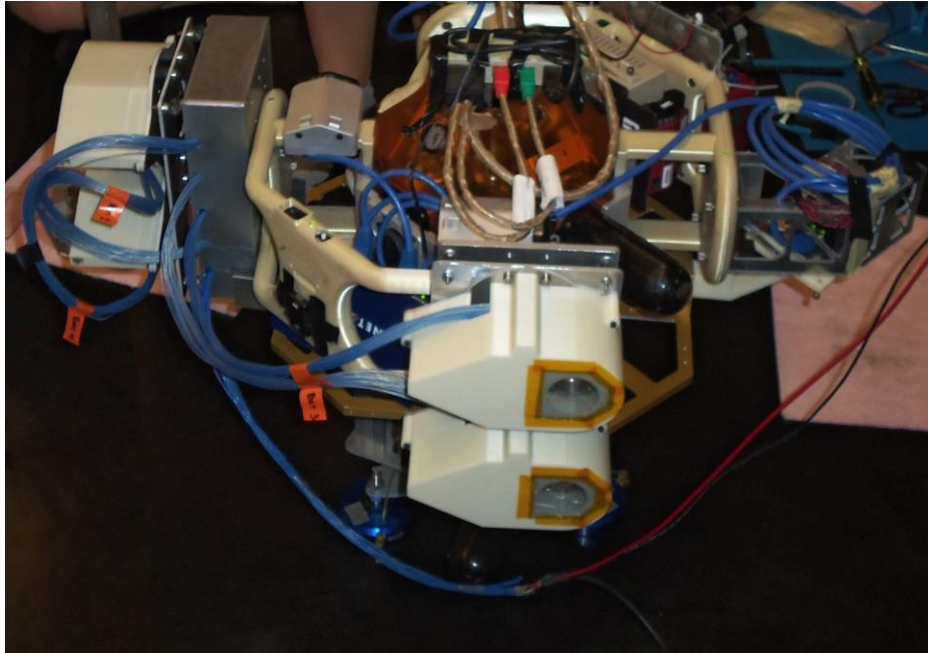


Figure 22: CMG External Power and Data Cables

Data lines in the Halo prototype are only functional for HPG (see Figure 30) as of May 2014, meaning that the INSPECT sensors and actuators had to stream their data through alternative connections for the duration of integrated testing. To accomplish this, the Optical Range Finder (ORF) and Thermographic Camera (ThermoCam) subsystems were connected via their respective Ethernet cables to a central Ethernet switch (Figure 92 and Figure 93), which was then connected via a third Ethernet cable to the functioning Ethernet port on HPG. The switch was stored adjacent to Halo Port #3, where it would not interfere with SPHERES thrusters. The location of the switch and sensor Ethernet cables are shown in Figure 23. The switch power cable, which was connected to a wall outlet, can be seen leading off from the vicinity of the switch in the top of the figure. Barely visible is the third Ethernet cable connecting the switch to the Ethernet port on HPG, which was run underneath the testing structure. The CMGs accomplished data transfer through a direct connection to a CMG-designated computer. The cables for this connection can be seen in Figure 22 (the red and black cable pair leading off in the right side of the figure). (KAF)

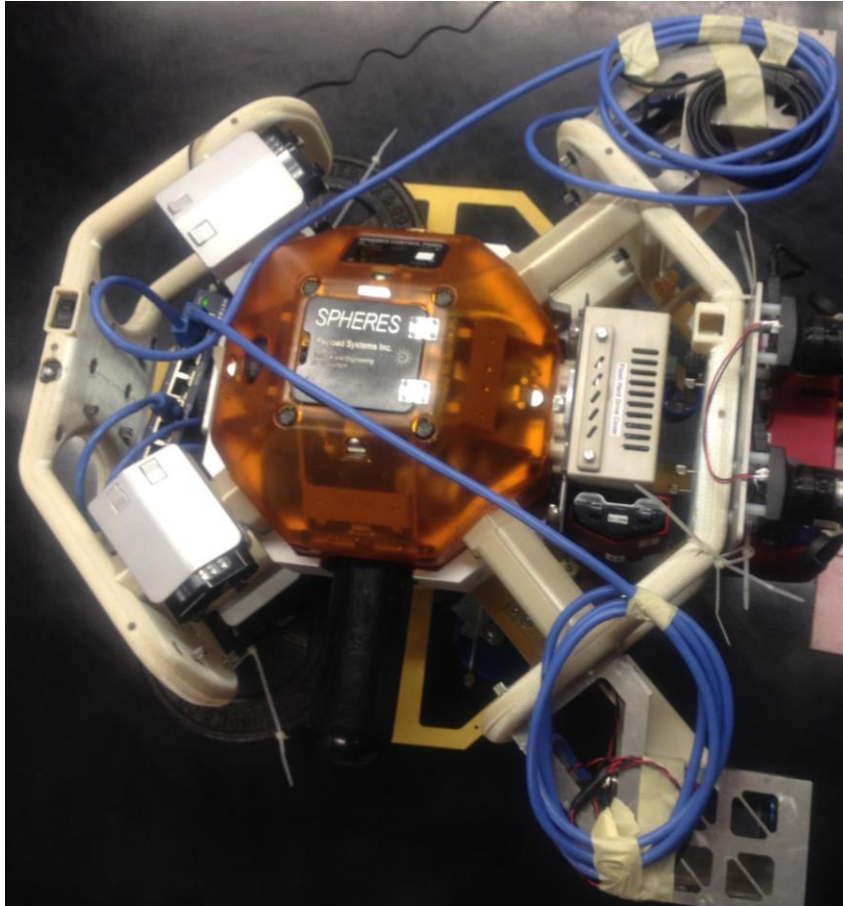


Figure 23: ORF, ThermoCam, and Ethernet switch connections

INSPECT also utilizes VERTIGO (Visual Estimation for Relative Tracking and Inspection of Generic Objects) to carry out observation and inspection tasks. VERTIGO, designed to interface with the SPHERES expansion port, includes an Avionics Stack (shown in white in Figure 24 (a)) with its own battery and processor. The Avionics Stack interacts with the Optics Mount (displayed in red in Figure 24 (a)), which houses two stereo cameras. VERTIGO is currently on the ISS and has proven functionality with SPHERES. Figure 24 (b) depicts VERTIGO as it currently integrates with SPHERES; in the INSPECT system, the Avionics Stack interfaces with SPHERES and fits inside the Halo structure (see Figure 21), while the Optics Mount connects to the corresponding Halo port (HPG), which routes power and data through Halo to the VERTIGO Avionics Stack. INSPECT incorporates VERTIGO into the integrated system to serve as one in a set of sensors to aid in observation, navigation, and inspection tasks. The utilization of VERTIGO in INSPECT is detailed in Section 4.1.2. (MK)

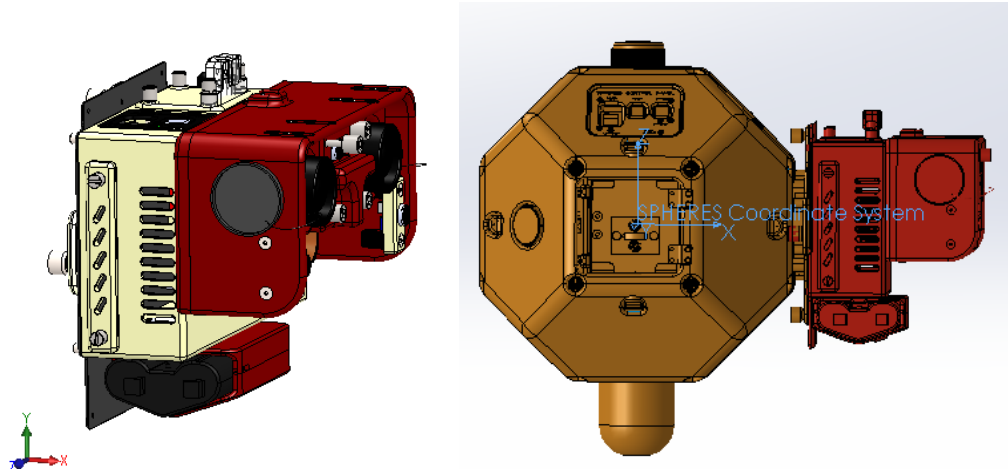


Figure 24 (a) and (b): VERTIGO Goggles Assembly (Avionics Stack with Optics Mount) [4] and Integrated SPHERES-VERTIGO System

The VERTIGO Optics Mount, normally connected through the Samtec 50-pin connectors on HPG, had an unexpected failure during testing, necessitating the use of an alternative Optics Mount. This alternative set of cameras was mounted on top of the existing Optics Mount and secured to Halo using two daisy chains of zip-ties. Each camera was provided power and data lines through its own USB cable, both of which were connected to the USB ports on the VERTIGO dongle. This restriction necessitated the continued connection of the dongle to both the INSPECT system and computer during testing; it was secured to the $-Y$ face of the SPHERES (Figure 20) with electrical tape, allowing for easy removal to access the SPHERES battery compartment also located on that face. While being secured, the dongle was carefully oriented so as to ensure no interference with the SPHERES thrusters in use. The dongle and alternative Optics Mount can be seen in Figure 25. (KAF)

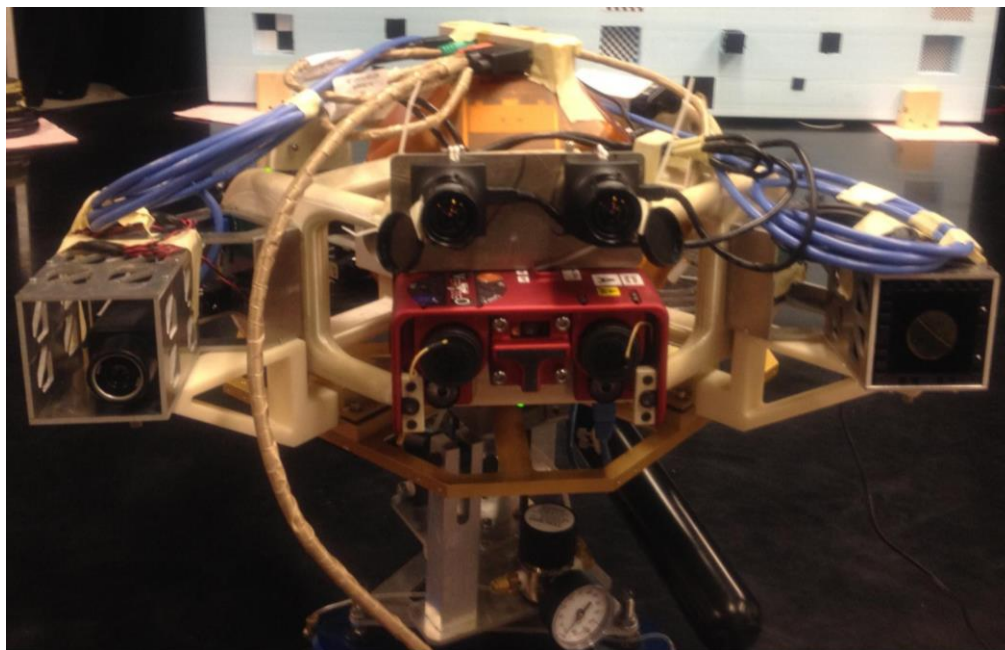


Figure 25: VERTIGO dongle and alternative Optics Mount secured to INSPECT

In order to provide attitude control, INSPECT incorporates two Control Moment Gyroscope (CMG) pairs. Figure 26 shows the integrated INSPECT system with CMGs (depicted with transparent enclosure covers) in a Box-90 configuration. A discussion of the CMG subsystem design is located in Section 4.1.5.

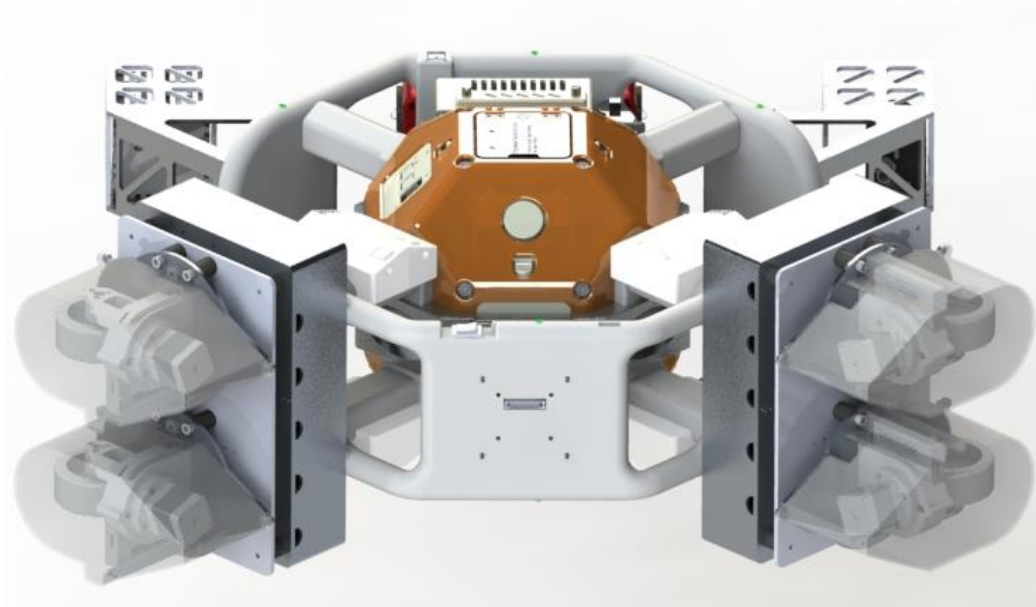


Figure 26: INSPECT, Integrated CMG Assembly View (Wiring Not Pictured) (JS)

Figure 27 displays the integrated INSPECT system with Optical Rangefinder and Thermographic Camera (pictured with mounting structures), VERTIGO Goggles, and CMGs. (MK)



Figure 27 (a) and (b): Integrated INSPECT System Configuration (Isometric and top views, respectively) (JS)

The final configuration used for integrated testing in May 2014 is displayed in Figure 28 and Figure 29. (KAF)

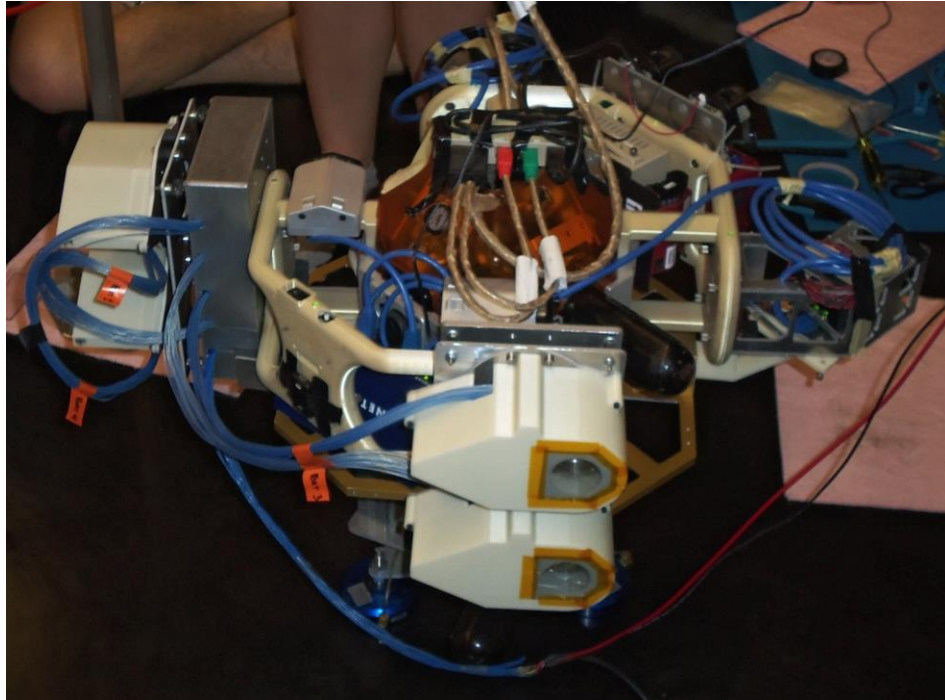


Figure 28: INSPECT Integrated Testing Configuration, May 2014 (rear view)

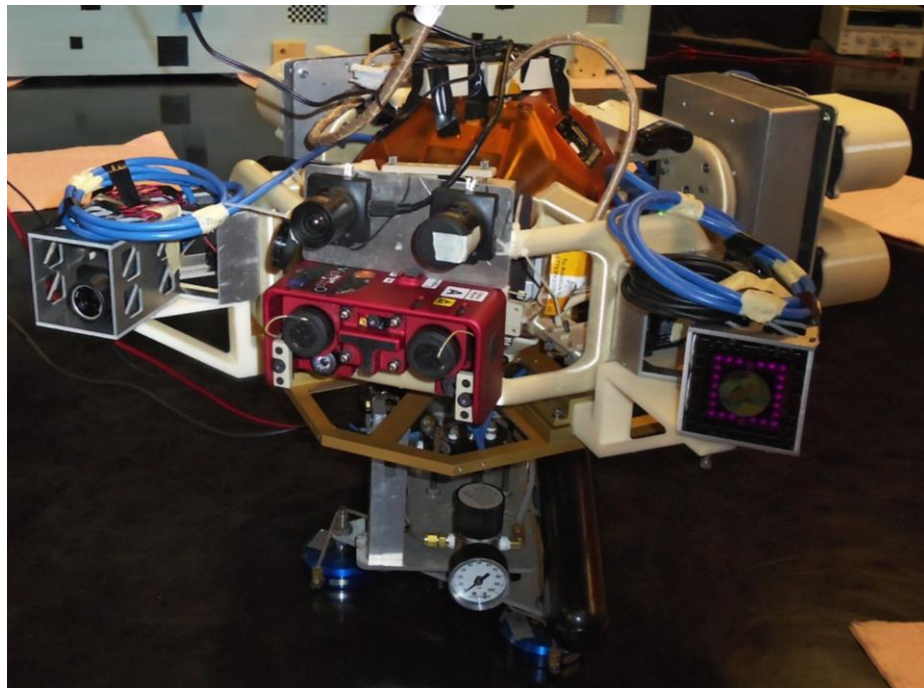


Figure 29: INSPECT Integrated Testing Configuration, May 2014 (front view)

3 System-Level Budget Allocations (MC, JB)

3.1 Mass (JB, MK)

Table 2: Mass Budget Allocation outlines the mass budget allocation of the INSPECT system, including the current best estimate (CBE) and margins of the subsystems. Note that the mass budget below does not include Halo and SPHERES masses, 4.525 kg and 4.828 kg, respectively (including batteries). In addition, masses in Table 2 do not include component wiring, which will reduce the total remaining mass when finalized.

Table 2: Mass Budget Allocation

Mass Budget

Subsystems (components and structures and avionics)	Allocated (kg)	Allocated Less 10% Margin (kg)	CBE (kg)	Remainin g (kg)	Remainin g (%)
VERTIGO	2	1.8	1.732	0.068	3.78%
Optical Rangefinder	2	1.8	0.828	0.972	54.00%
Thermographic Camera	1	0.9	0.419	0.481	53.44%
CMGs	6	5.4	5.1	0.3	5.56%
Total Allocated Mass (kg)			11		
Total Allocated Mass Less 10% Margin (kg)			9.9		
Total CBE Mass (kg)			8.079		
Total Remaining (kg, %)			1.82	18.39%	

3.2 Power (JB)

Table 3: Power Budget Allocation outlines the power budget allocation (in terms of average and peak power) of the INSPECT system, including the current best estimate (CBE) and margins of the subsystems.

Table 3: Power Budget Allocation

Power Budget

Sub- systems	Allocated Peak Power (W)	Allocated Less 10% Margin (W)	CBE Avg Power (W)	Remaining		CBE Peak Power (W)	Remaining	
				(W)	(%)		(W)	(%)
VERTIGO Optics Mount	5	4.5	1.4	3.1	68.89%	4.5	0	0.00%

Optical Range-finder	16.5	14.85	5.27	9.58	64.51%	6.52	8.33	56.09%
Thermo-graphic Camera	16.5	14.85	3	11.85	79.80%	12.12	2.73	18.38%
CMGs	16.5	14.85	7	7.85	52.86%	11	3.85	25.93%
Total Allocated Power (W)					54.5			
Total Allocated Power Less 10% Margin (W)					49.05			
Total CBE Average Power (W)					16.67			
Total Remaining (W, %)					32.38	66.01%		
Total CBE Peak Power (W)					34.14			
Total Remaining (W, %)					14.91	30.40%		

3.3 Data Rate and Data Processing (JB)

Table 4: Data Rate Budget Allocation outlines the data rate budget allocation of the INSPECT system. The Halo structure provides a single split Ethernet connection (4 twisted pairs) and a single split USB 2.0 connection on each Halo port, and a single split Ethernet connection and two designated USB 2.0 connections on the Halo port pre-designated for the VERTIGO Optics Mount (HPG), as outlined. The amount of data that can flow through these connections well exceeds the data that each subsystem will transmit (more details available in Section 4.2.5).

Table 4: Data Rate Budget Allocation

Data Rate Budget

Subsystems	Allocated Data Rate (Mbps)	Allocated Less 10% Margin	CBE (Mbps)	Remaining		Allocated Data Connection
				(Mbps)	(%)	
VERTIGO	320	288	7.22	280.78	97.49%	2x USB 2.0
Optical Rangefinder	500	450	0.812	449.188	99.82%	1x Ethernet
Thermographic Camera	500	450	4.3	445.7	99.04%	1x Ethernet
CMGs	160	144	1	143	99.31%	1x USB 2.0
TOTAL	1480	1332	13.332	1318.668	99.00%	

Table 5: Data Processing Budget Allocation outlines the budgeted Data Processing in units of milliseconds. The on-board computer utilized by INSPECT (and outlined in section 4.1.2.1.1) operates on a 1Hz cycle (it completes one cycle of processing every second). This frequency

dictates a maximum total processing time for all combined systems (including on-board SPHERES processing, thrusting, etc) of 1000ms.

Table 5: Data Processing Budget Allocation

Data Processing Budget

Subsystems	Allocated Processor Time (ms)	Allocated Less 10% Margin	CBE (ms)	Remaining		Allocated Data Connection
				(ms)	(%)	
VERTIGO Optics Mount	300	270	220	50	18.52%	2x USB 2.0
Optical Rangefinder	200	180	110	70	38.89%	1x Ethernet
Thermographic Camera	150	135	70	65	48.15%	1x Ethernet
CMGs	50	45	10	35	77.78%	1x USB 2.0
Navigation (Localization Algorithm)	300	270	270	0	0.00%	
TOTAL	1000	900	680	220	24.44%	

3.4 Finances (JB)

Table 6: Financial Budget Allocation outlines the cost budget allocation of the INSPECT system, including the current best estimate (CBE) and margins of the subsystems.

Table 6: Financial Budget Allocation

Subsystems (components and structures and avionics)	Allocated (\$)	Allocated Less 10% Margin (\$)	CBE (\$)	Remaining (\$)	Remaining (%)
VERTIGO	500	450	1525	-1075	-238.89%
Optical Rangefinder	7500	6750	4092.335	2657.665	39.37%
Thermographic Camera	4500	4050	2312.495	1737.505	42.90%
CMGs	3000	2700	66.2	2633.8	97.55%
Structures	7000	6300	292.43	6007.57	95.36%
Electronics	3000	2700	2706.53	-6.53	-0.24%
Unallocated	14000				
Total Allocated Cost (\$)			25500		
Total Allocated Cost Less 10% Margin (\$)			22950		
Total CBE Cost (\$)			10994.99		
Total Remaining (\$, %)			11955.01		52.09%

4 Subsystem Design

4.1 Payload

4.1.1 Halo on SPHERES (JB)

4.1.1.1 Driving Requirements and Purpose/Relevance to INSPECT (JB)

Halo is designed to support up to six different sensor and actuator peripheral systems, including the sensors and actuators used by INSPECT. Mechanically, it facilitates the physical connection

of up to six peripheral systems surrounding the SPHERES platform, while simultaneously leaving open channels for thruster plumes to propel the SPHERES. Electrically, Halo facilitates connection to the VERTIGO Avionics Stack and internal SPHERES DSP and data routing, as well as both regulated and unregulated voltage and current via four on-board battery packs.

Halo enables all INSPECT subsystems to be simultaneously connected to SPHERES and the VERTIGO Avionics Stack, and peer-to-peer to one another via an Ethernet or USB switch. For this reason, INSPECT requires that Halo have both Ethernet and USB data lines on the Halo ports to support its sensors.

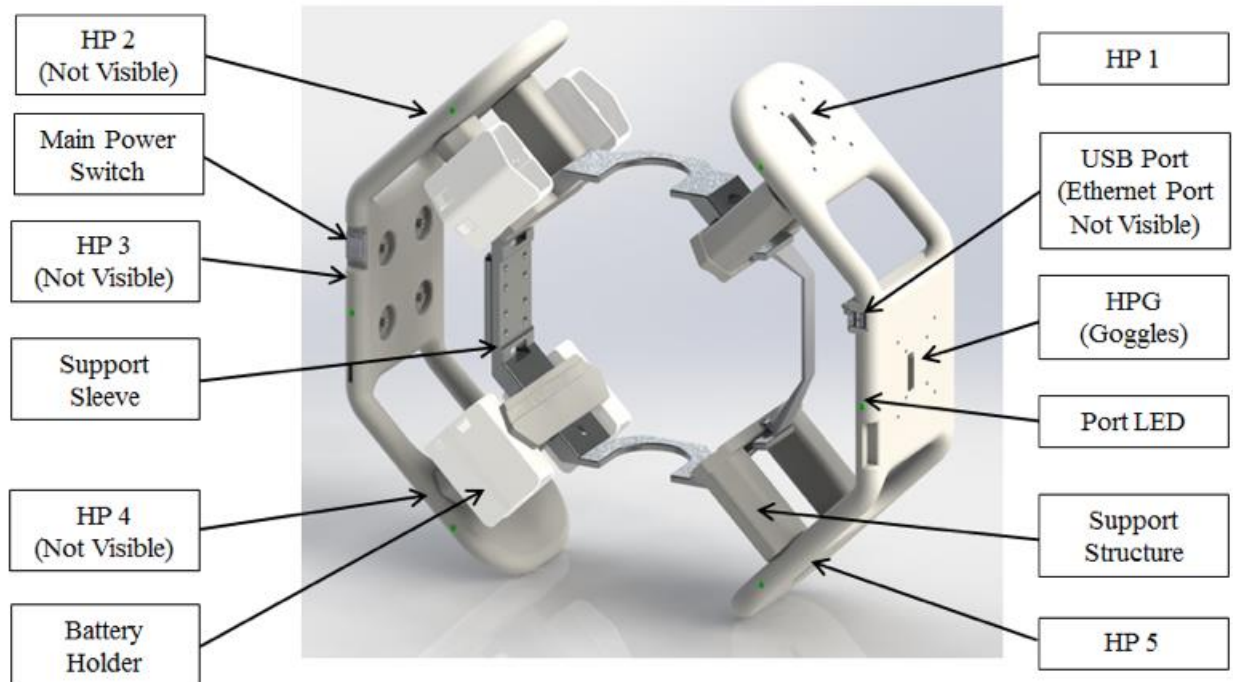


Figure 30: Halo Overall Layout [5]

4.1.1.2 Design Choice (JB)

The specific Halo design choice was made by 2nd Lt. Bryan McCarthy, USAF, and the Space Systems Lab at MIT. [5]

Halo was chosen as a platform for INSPECT due to its uniqueness as a cohesive platform where multiple subsystems can be tested and operated simultaneously, while also providing a means of combining and overlaying data collected from each subsystem in a central computer. It has been developed specifically for the purpose of facilitating sensor and actuator suites such as INSPECT. The power system supplied by Halo also enables greater mission duration and range of sensors and actuators than the much reduced power output available on SPHERES. Finally, Halo's 45° angled ports facilitates a Box 90 configuration for efficient deployment of the CMGs, as shown in Figure 57.

4.1.1.3 Structures (JB)

Halo provides six Halo ports in a symmetrical pattern about the SPHERES platform. Each Halo port consists of a 50 pin Samtec ERF8-025-01-S-D-RA-TR female connector located at the center of two distinct square-shaped mounting patterns. The inner mounting pattern (in Figure

31), designed for use on the two central Halo ports (Halo Port #3 and HPG) enables screws to be drilled from outside the Halo port, inward. Alternately, and designed for use on the four peripheral Halo ports (Halo Ports #1, #2, #4, and #5), male screws protrude from the port enabling mounting of subsystems by screws drilling outboard away from SPHERES, avoiding the wasted space caused by outboard-to-inboard male screw insertion.

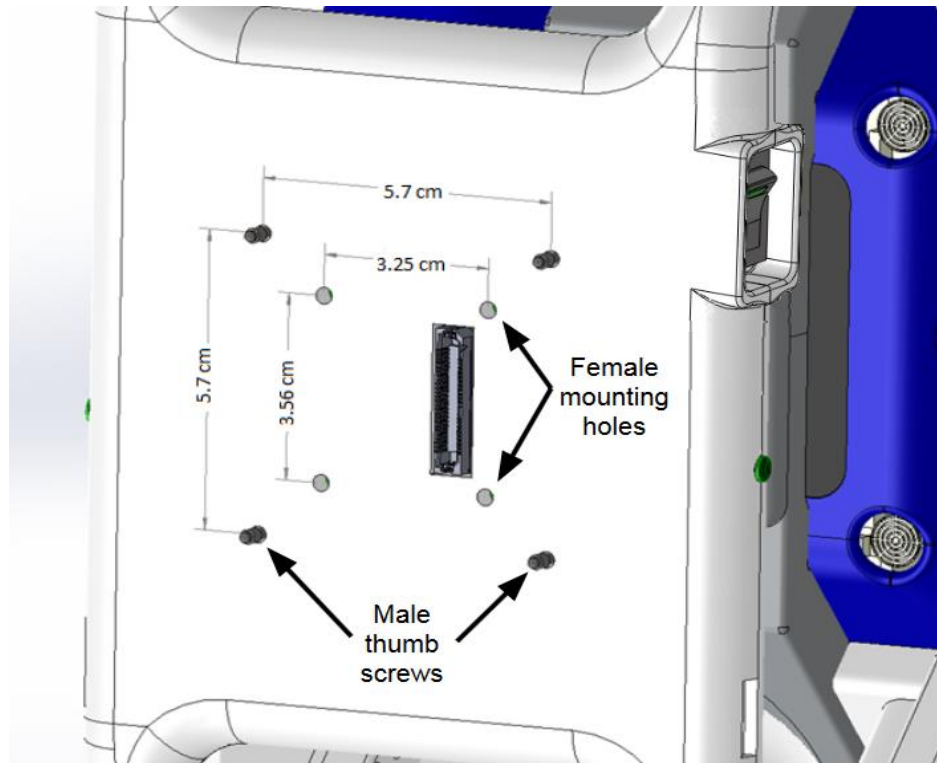


Figure 31: Halo Port Footprint, Rotated 90° Clockwise [5] (JB)

4.1.1.4 Power and Interfaces (JB)

The Halo port interface supports a 50 pin Samtec ERF8-025-01-S-D-RA-TR connector (Figure 73), with pins S-1, 3, 5, 7, 9, and 11 for power. S-1, 3, and 5 connect directly to the negative end of the Halo battery suite, and S-7, 9, and 11 connect directly to the positive terminal. The total voltage provided out of these six combined pins is 11.1V, at a maximum current of 1.5A per port. Once 7.5A total is pulled from the batteries as a combined load from all six Halo ports, a PPTC fuse resets and power is cut to the system. Similarly, at each Halo port, once 1.5A is exceeded, another PPTC fuse resets that individual Halo port, without impacting any other Halo ports. Ground terminals are also present on the 50-pin connector, at pins S-2, 21, 37, 40, 43, 46, and 49.

Pin 1 of the female 50-pin connector embedded in the Halo port is located on the top right of the connector when looking directly at the Halo port, outboard to inboard.

More information on Halo's power and interfaces can be found in the Halo Design Document.

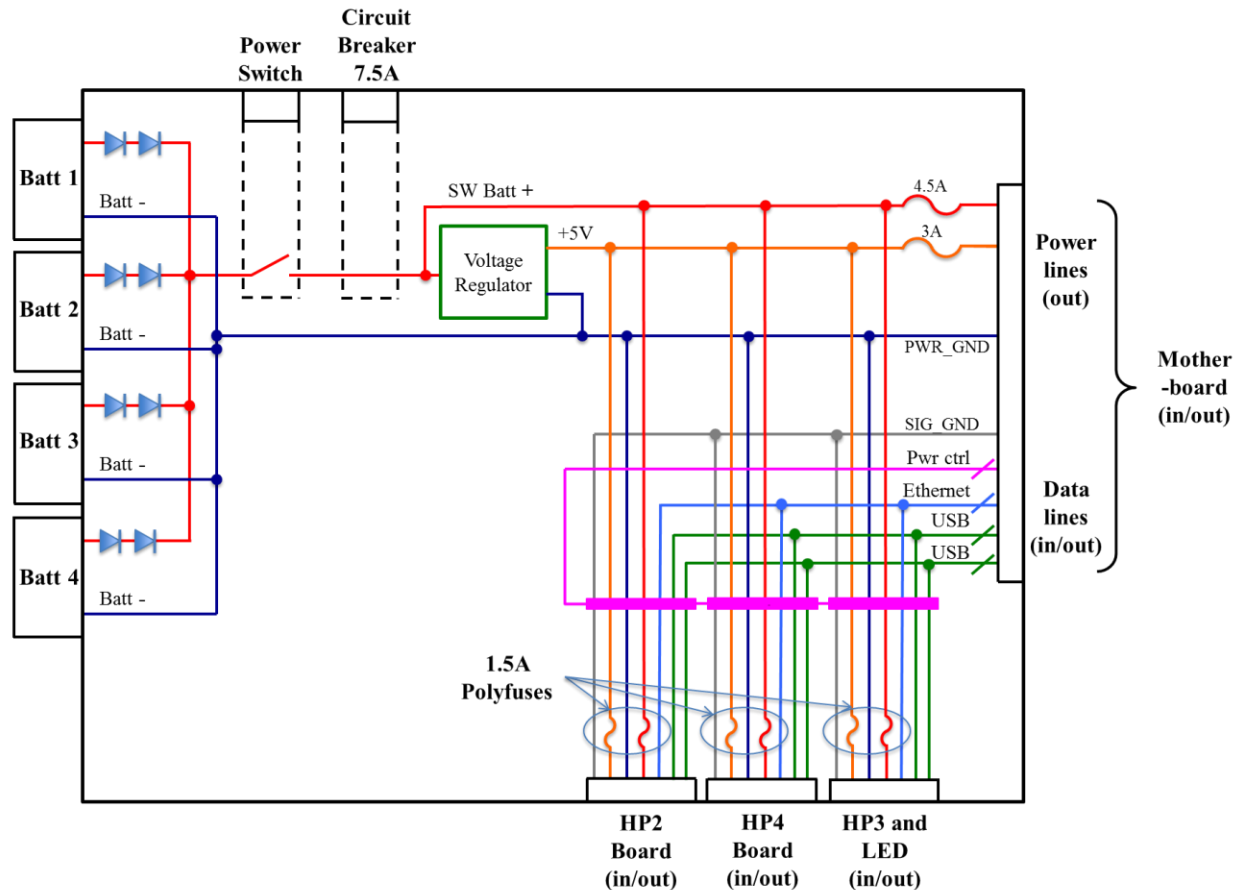


Figure 32: Halo Power Board Circuitry [5]

4.1.1.5 Data and Interfaces (JB)

The positive X axis of the SPHERES platform connects via the expansion port to the VERTIGO Avionics Stack, which provides computation and data routing for all six Halo ports. The Samtec ERF8-025-01-S-D-RA-TR on each port (Figure 73) has Ethernet pin pairs at S-39 & 41, 42 & 44, 45 & 47, and 48 & 50, with a ground pin next to each Ethernet pair. It also has USB pin pairs at S-4 & 6 and 10 & 12. UART pin pairs are found at S-22 & 24 and 30 & 32 for connection to the SPHERES DSP.

The Ethernet pins serve as one of two data transport system, transporting data via pin pairs 1&2, 3&6, 4&5, and 7&8. The Control Moment Gyroscopes (CMGs) utilize a control board which interfaces via an RSS 422 connector. This necessitates the use of an additional Printed Circuit Board (PCB) to transfer data to USB and connect the male Samtec ERM8-025-09.0-S-DV-K-TR to the female connector on the Avionics Stack, ERF8-025-01-S-D-RA-TR. This design is discussed in detail in section 4.1.5.5.

More information on Halo's data interfaces can be found in the Halo Design Document.

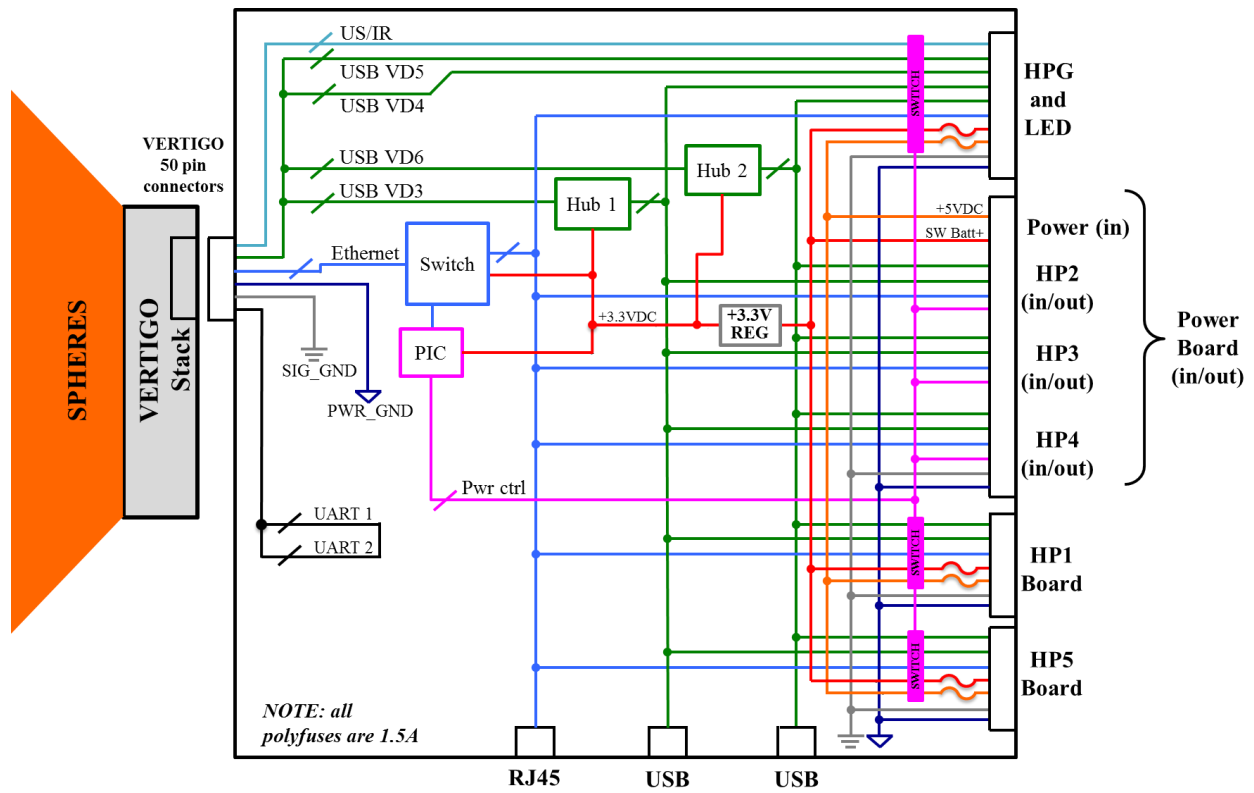


Figure 33: Halo Motherboard Circuitry [5]

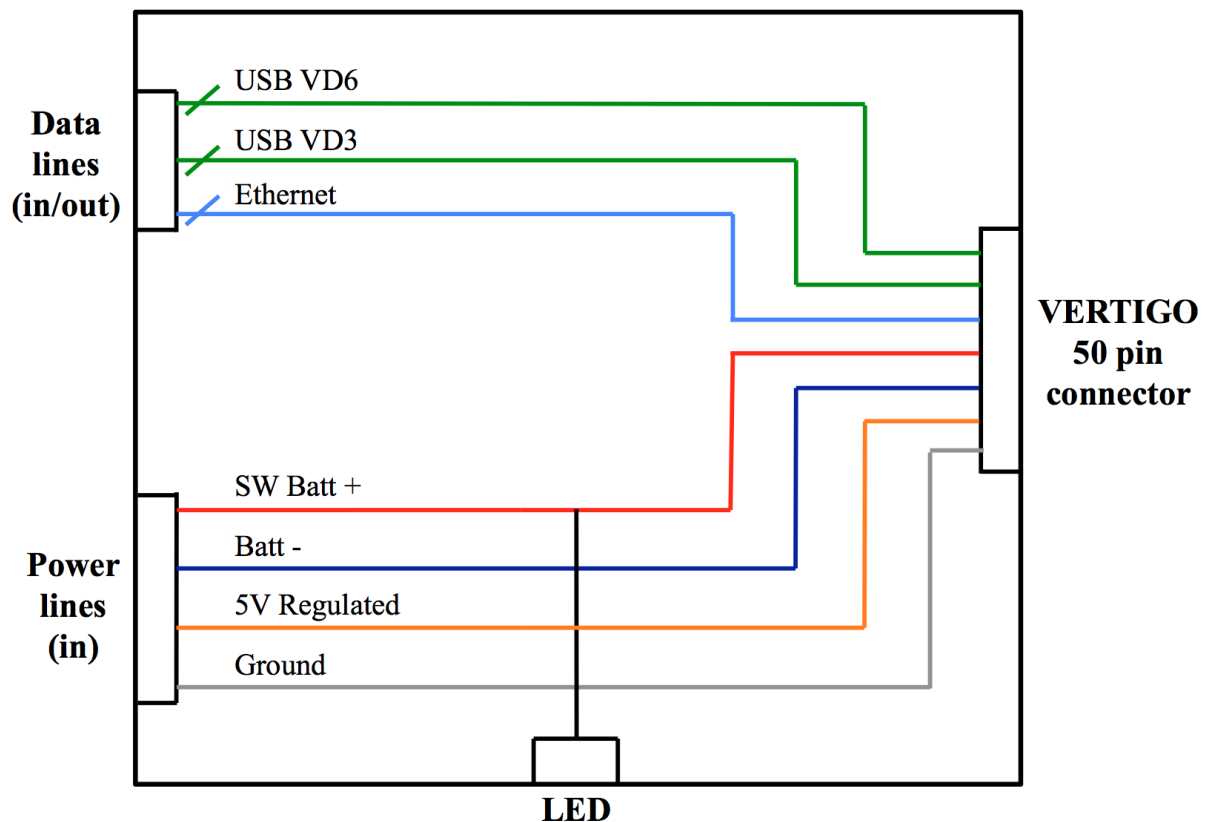


Figure 34: Halo Port Circuitry [5]Printed Circuit Board (JB, CK, CL, GP)

A printed circuit board (PCB) acts as an interface between the peripheral subsystem sensors and their respective Halo ports, facilitating the appropriate routing of both power and data signals. The Multiple Interface Control PCB (MICPCB) board layout used for integrated testing can be found in Figure 35. This version is a simplified version of the MICPCB shown in Figure 37: MIC PCB with health monitoring system (GP, CL, CK). The decision to use the simplified version for testing was made in the interest of streamlining whole system integration rather than devoting time to performing additional testing of the MICPCB health monitoring system. The intent is that the MIC PCB with the health monitoring system will be used in further testing and development of INSPECT. The MICPCB with health monitoring and without health monitoring have identical essential components, including the voltage regulator, screw terminal, and Ethernet connector, which is why testing without the health monitoring system was deemed appropriate for the current INSPECT prototype (CK).

The MICPCB is designed to serve as the PCB for both the Optical Rangefinder (ORF) sensor as well as the Thermographic Camera (ThermoCam). This enables the MICPCB design to be mass-produced at a lower price and interchanged between the various sensors. (CL)

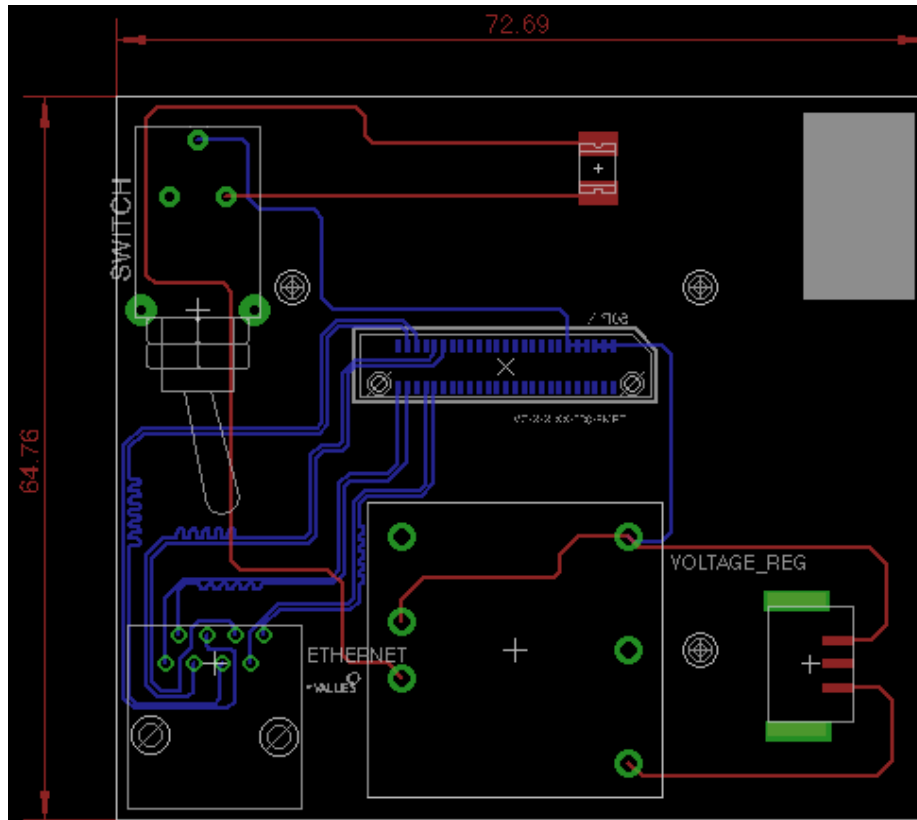


Figure 35: Multiple Interface Connection PCB (MIC PCB) (CL, CK, GP)

The MICPCB has three main functions: route power, route data, and in the version with health monitoring, monitor and indicate health of power to sensor. The MICPCB has one switch to provide power to the entire board, and because the ThermoCam and ORF will each have their own PCB, each sensor can be turned on or off independently using the PCB or using the power switch on each Halo port. However, as of May 2014, Halo does not have functioning individual power switches, so the ORF and ThermoCam were independently switched on via the switches on the PCB. In the health monitoring version, a lit green LED will serve as a visual indicator when the board is turned on and there is power at the output of the voltage regulator (i.e power available for the attached sensor); this can be seen in the health monitoring PCB just before the screw terminal which delivers power to the sensor. In addition, the health monitoring version also features a red LED which lights up when a fuse is tripped, indicating a problem and no power being delivered to the sensor. As of May 2014, the MICPCB was tested and integrated into the entire system but without any LED indicators due to an assembly error and in the interest of streamlining integration (CK, CL).

Power is routed from Halo over pins 1, 3, 5, 7, 9, and 11 on the Samtec 50-pin ERM8-025-09.0-S-DV-K-TR male connector and into a Delta S24SE12002PDFA DC-DC power regulator with 9-36V input, 12V output and 20W rating. Pins 1, 3, and 5 serve as ground (BATT-) on the 50-pin connector, and pins 7, 9, and 11 serve as power (BATT+) that provide the 11.1V to power the MICPCB. The voltage and current entering the voltage regulator is set at 11.1V and 1.5A, and the regulator steps up the voltage to the 12V required by both the MESA SR4000 and the FLIR A5 Thermographic Camera. The now-regulated voltage from Halo is directly transmitted to the sensors via a 3-port screw terminal and a connection cable. The ORF connects to this screw terminal via a Lumberg M8 3-pin cable, and the ThermoCam connects via an M12 connector

(CK). The wires for power, shield, and ground on each connector will connect to the appropriate ports on the screw terminal to power the sensors. (CL)

Data is routed into and out of the MICPCB via a Samtec ERM8-025-09.0-S-DV-K-TR 50-pin male connector over pairs 45 & 47, 48 & 50, 42 & 44, and 39 & 41 to Ethernet pin pairs 4 & 5, 2 & 1, 8 & 7, and 6 & 3 for both the ORF and the ThermoCam. Because the board is intended for use by both sensors, all eight Ethernet pins must be connected, even if only four are used for data transmission, as is the case with the ORF. As of May 2014, Halo does not have working data connection in any of the ports other than the HPG port that VERTIGO connects into, so no data will be transferred via the Ethernet pins on the MICPCB. Instead, both the ORF and the ThermoCam will transmit data through a central Ethernet switch that is connected to the VERTIGO Avionics Stack. More detail on this configuration is detailed in Section 6.2.5. The intent is to use the same Ethernet connector on the current MICPCBs in the future to route data through the MICPCB, after testing has been completed. (CL, CK)

Health monitoring is performed via a polymeric positive temperature coefficient device (PPTC) resettable fuse for the power loop. Two lines run parallel to the main load, connected by the fuse. An LED (separate from and colored differently from the “power on” LED; in this case colored red) is connected to the loop which does not depend on the fuse for power, and will remain unlit until the fuse is blown, at which time it will light up and display a warning that the sensor has failed and is no longer connected to power. The second parallel loop keeps the LED un-lit during normal operation by means of a diode to the base of the type P-N-P binary transistor which straddles the two parallel loops. In order to resume functionality, all power must be cut and reset to the system by turning the Halo port off and then back on. However, due to difficulties resolving issues with the health monitoring system, the health monitoring portion of the circuit was not populated beyond the fuse during MICPCB testing and integrated systems testing (see Figure 35 or Figure 36). (CL) During MICPCB testing, it was found that the S24SE12002PDFA voltage regulator acts as a protector for the sensors, because it resets its current draw to 0A if the current approaches about 1.5A. This was deemed sufficient and appropriate to protect the sensors, and the health monitoring system was deemed not absolutely necessary for integration of the MICPCB with each sensor. In the future, a health monitoring system will be implemented on the MICPCBs for each sensor, as seen in Figure 37. (CK)

Table 7 shows all components for the MICPCB, but since the health monitoring section of the PCB was not populated, the 910 Ω and 51k Ω resistors, diode, PNP transistor, and LED were not used in the tested and integrated iteration of the MICPCBs. The intent is to use these components to populate and test future iterations of the PCBs with the health monitoring system implemented. (CL, CK)

The schematic of the integrated and tested MICPCB is displayed in Figure 36. The layout and schematic of the MICPCB with a health-monitoring system are shown in Figure 37 and Figure 38.

Table 7: MIC PCB Populating Components (CK, CL)

Component	Description	Part Number
Samtec 50-Pin Connector	Connects to the Halo 50-pin port	ERM8-025-09.0-S-DV-K-TR
910 Ω Resistor	Resistor as part of health-monitoring system	ESR18EZPJ911
51 k Ω Resistor	Resistor as part of health-monitoring system	RC1206JR-0751KL
Diode	Diode as part of health-monitoring	1N4148WS

	system	
Gigabit Ethernet Connector	Connects to ORF and ThermoCam Ethernet cables for data transfer	SS-7188V-A-NF
Switch	Turns the MIC PCB on and off	21136NA
3-Hole Screw Terminal	Connects MIC PCB to ORF and the ThermoCam	1771101
PNP Transistor	PNP transistor as part of health-monitoring system	2DB1694-7
LED	Visual indicator when PCB is powered and when fuse has been tripped	597-3311-407F
PPTC Fuse	Current-limited resettable fuse as part of health-monitoring system	1812L075/24DR
Voltage Regulator	Step-up 11.1V input from Halo to 12V required for ORF and ThermoCam	S24SE12002PDFA

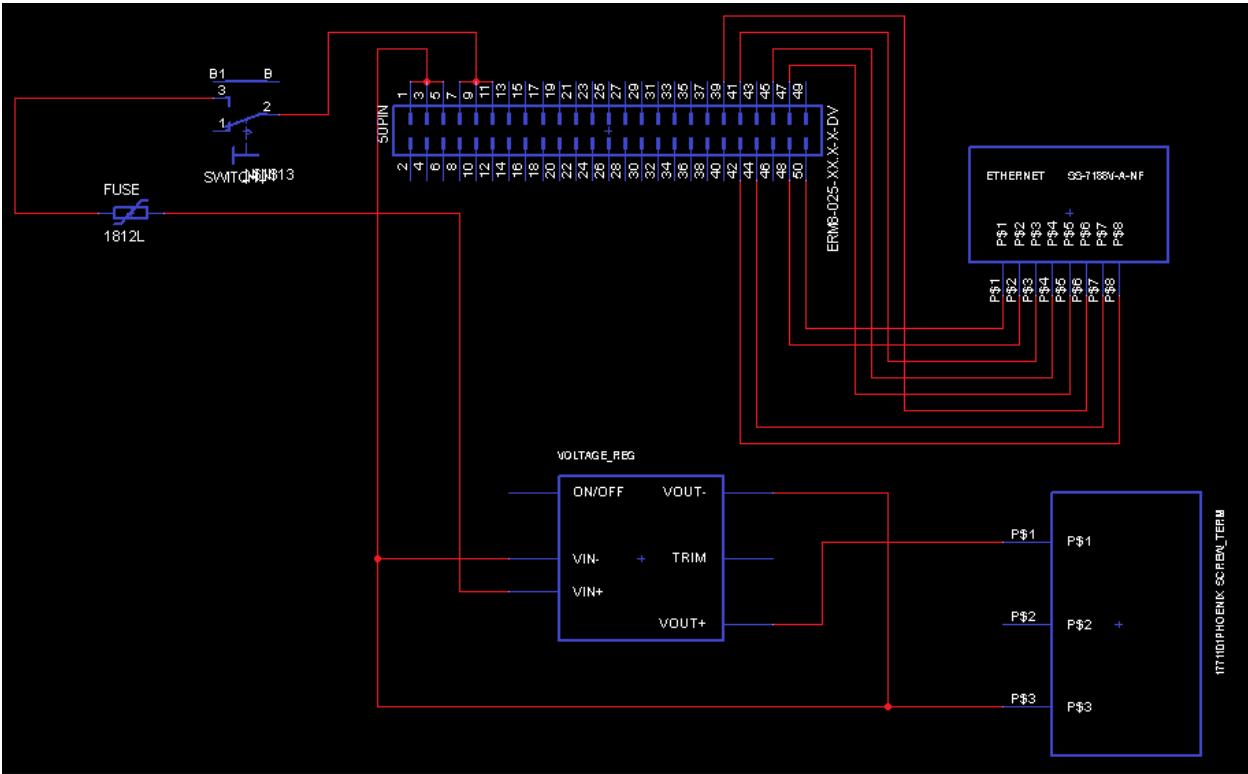


Figure 36: MIC PCB Testing Schematic (CL, CK)

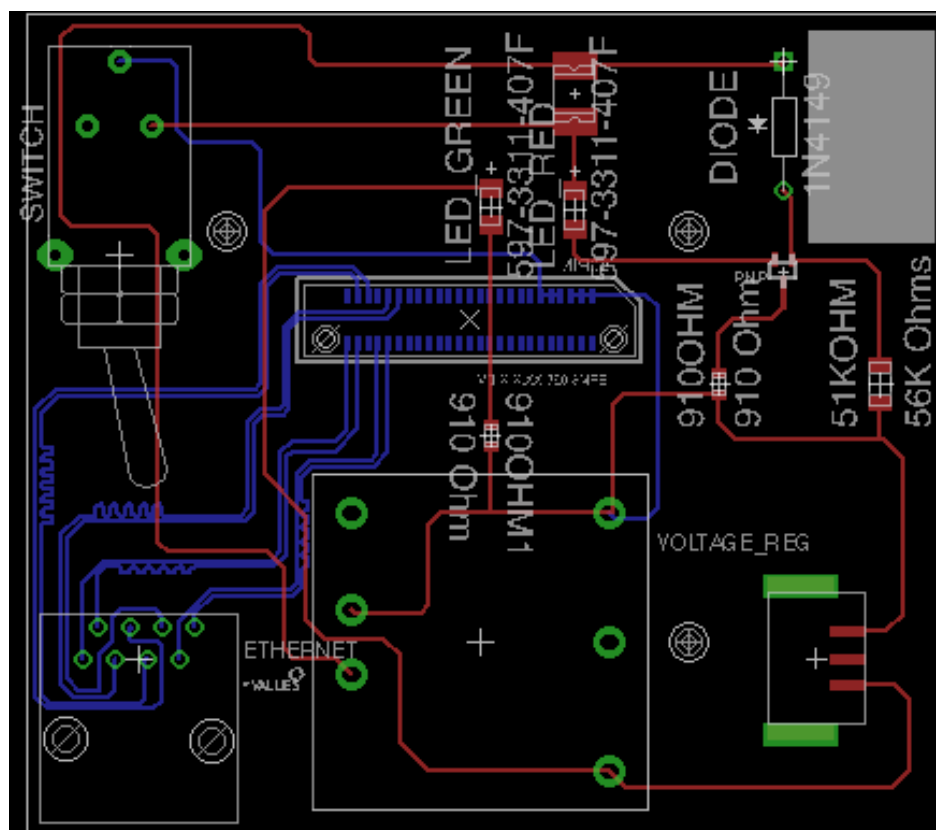


Figure 37: MIC PCB with health monitoring system (GP, CL, CK)

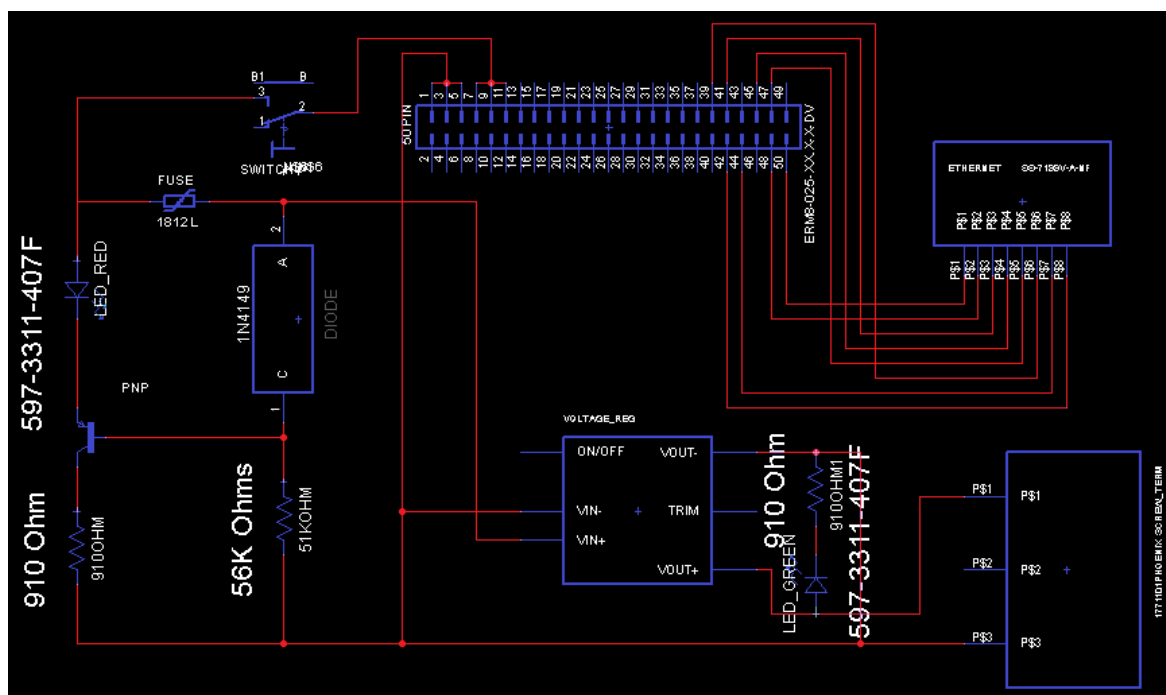


Figure 38: MIC PCB schematic with health monitoring system (GP, CL, CK)

4.1.1.7 Software

Halo facilitates a connection to the VERTIGO Avionics Box and DSP on the SPHERES internal CPU, thereby giving INSPECT access to the VERTIGO software for processing guest scientist algorithms and commanding SPHERES.

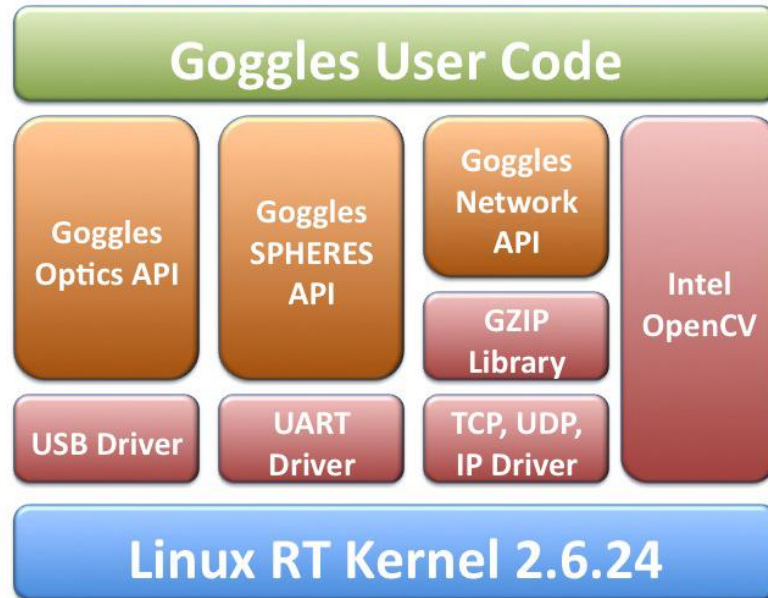


Figure 6: VERTIGO Avionics Software Architecture [6]

4.1.1.8 Mass

4.1.1.9 The total Mass of Halo is 4.525kg, including batteries. [5]

4.1.1.10 Financial Budget

The Halo will be considered a commercial off-the-shelf (COTS) product, as all costs will be incurred by 2nd Lt Bryan McCarthy's team and the MIT Space Systems Lab.

4.1.2 VERTIGO Goggles (AL, HL)

4.1.2.1 Description

The VERTIGO Goggles are comprised of two pieces of hardware: the Optics Mount and Avionics Stack, that come together to make the system referred to as the *VERTIGO Goggles*

4.1.2.1.1 VERTIGO Avionics Stack

The VERTIGO Avionics Stack is comprised of the tan-colored square enclosure which houses VERTIGO's CPU, hard drives, operating system, and wi-fi network components. It acts as the computer for the VERTIGO Goggles, handling all of the image processing and sensor commands for the subsystem [6]. It runs Linux Ubuntu 10.04 as its operating system. In relation to INSPECT, the Avionics Stack will handle inputs from all the peripheral systems in addition to the Goggles (including the ThermoCam and the ORF) as well as route information to the SPHERES from the CMGs.

4.1.2.1.2 VERTIGO Optics Mount

The VERTIGO Optics Mount acts as the main sensor of VERTIGO, acting as physical housing for two stereoscopic cameras. It also contains the input ports for VERTIGO (one

Ethernet and two USB 2.0 ports) as well as LED lights for environment lighting.

4.1.2.2 Driving Requirements and Relevance to INSPECT (AL)

The driving requirements for including VERTIGO as a payload for INSPECT are listed in Table 8: VERTIGO Driving Requirements. These requirements concern the VERTIGO Optics Mount in its capacity as a distinct peripheral sensor system in INSPECT. The first three requirements (ID prefix SEN) define the scope of the Optics Mount sensor, while the other requirements ensure that the sensor can interface with the rest of the system.

Table 8: VERTIGO Driving Requirements

SEN-1	Field of View	All imaging sensors shall have a minimum field of view of 33 degrees by 33 degrees.	SX-1, SX-2	Expectation of 30 degree rotation per image sequence with 10% overlap	Testing
SEN-2	Target Distance	The system shall determine the distance to a target object accurate to within 10 cm with precision to 2 cm up to 10 meters away	SX-1, SX-2	Defines ranging limits	Testing
SEN-3	Visible Light Image	The system shall resolve a visible-light image of a 1cm per pixel resolution from 1 m	SX-1, SX-2	Defines optical resolution limits.	Testing
SEN-4	Sensor Data	All sensors shall send data at a rate which can be processed by the VERTIGO computer or must include its own computer for data processing	SX-4	Need to transfer data	Testing
SEN-5	Thermal Image	The system shall resolve a thermal image of a 5x5 cm object from a distance of 1 m to +/- 5 degrees C accuracy and a noise equivalence temperature difference of <1 degree C at 20 degrees C.	SX-1, SX-2	Defines thermal resolution limits and accuracy/precision to produce a reasonable thermal image for our purposes.	Testing
SEN-6	Pose Sensors	The system shall be able to determine its pose in 2 dimensional space with 1 axis of rotation normal to the test floor	SX-1, SX-2, SX-5	Ability to support guest scientist navigation algorithms necessitates navigational sensors	Testing

4.1.2.3 Design Choice (AL)

The VERTIGO system was selected for use in INSPECT for its ability to serve both as a peripheral sensory system (Optics Mount) and the ability to serve as the main processing platform for all of the peripheral systems (Avionics Stack). It has already been test and verified to function effectively with the SPHERES platform, which means that it would expectantly require less initial development to become compatible with INSPECT than another brand new system.

4.1.2.4 Structures (AL)

The VERTIGO system requires no additional structural components to be assembled in order to be incorporated into INSPECT. The Halo system fully supports integration of the VERTIGO system during operation.

4.1.2.5 Mass (JB, AL, HS)

The mass characteristics of the VERTIGO system are listed below in Table 9: VERTIGO Component Masses.

Table 9: VERTIGO Component Masses

Mass Budget:		1.8kg
Item	Mass (kg)	Notes
Avionics Stack	0.82	
Optics Mount	0.73	
Nikon EN-EL4 Battery	0.162	
Total Spent:	1.732	
Budget Remaining:	3.7%	

4.1.2.6 Power and Interfaces (JB, AL,HS)

Table 10: VERTIGO Peak Power Budget

Peak Power Budget:		16.5W
Item	Power (W)	Notes
Optics Mount	1.3	For 2 cameras
Avionics Stack	6.8	
Total Spent:	8.1	
Budget Remaining:	50.9%	

Table 11: VERTIGO Average Power Budget

Average Power Budget:		5.5W
Item	Power (W)	Notes
Optics Mount	0.575	
Avionics Stack	6.8	
Total Spent:	7.95	
Budget Remaining:		

4.1.2.7 Data and Interfaces (JB, AL)

Table 12: VERTIGO Data Rate Budget

Data Rate Budget:		320Mbps
	Rate (Mbps)	Notes
Total Spent:	10.8288	
Budget Remaining:	96.6%	

Table 13: VERTIGO Data Rate Budget

Data Processing Budget:		300ms
	Time (ms)	Notes

Total Spent:		
Budget Remaining:		

4.1.2.8 Software (HL)

The VERTIGO software system consists of Goggles Optics Mount API and Goggles Avionics Stack API, and Goggles SPHERES API. However, VERTIGO Goggles software structure is mainly focused on Avionics Stack API. As a core system for INSPECT, Avionics Stack provides both hardware and two-way (command and receive) software connections between SPHERES DSP and INSPECT peripheral imaging sensors.

The main functionalities include image processing and a pre-emption of data inputs from VERTIGO Optics Mount, ThermoCam, and ORF. The VERTIGO Goggles system also provides formatted sensor data to GSP via Goggles API. Using these data, guest scientists can prioritize the sensor inputs based on their own program of interest.

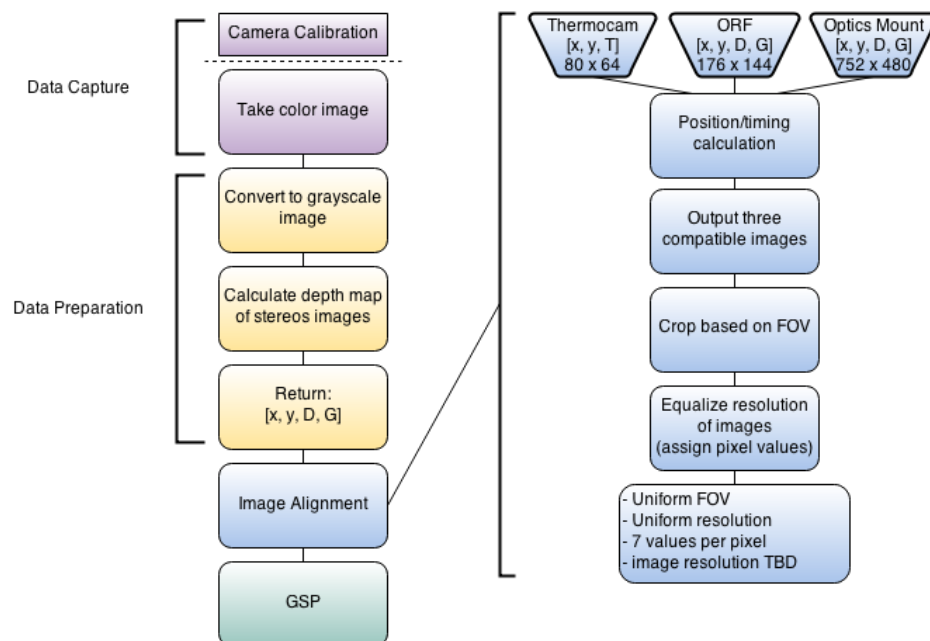


Figure 39: VERTIGO Avionics Stack Software Data Flow Diagram

Figure 33 illustrates the data flow diagram specifically for the VERTIGO Optics Mount. The Optics Mount goes through data capture, data preparation, image alignment, and GSP procedures. For 16.83x INSPECT, the major requirements were to implement and verify the data capture, the data preparation, and transfer data to image alignment procedure.

A rough estimate of FLOPs necessary to perform the software operation outline in Figure 39: VERTIGO Avionics Stack Software Data Flow Diagram, was determined using the assumption that the number of transformations necessary to align the three images was on the order of one. Alignment consists of matching an image from each sensor to existing images from another so that each single 5D voxel frame of a scene consists of 3 distinct frames from each sensor (with the ORF providing three values per pixel). These calculations were used to determine that a 1 HZ cycle of the sensors – to match what was imposed by SPHERES -- was possible given the hardware. (GP)

4.1.2.9 VERTIGO Emulation (HL)

VERTIGO Emulation provides the same software environment as that of the actual Avionics Stack, but on different hardware, such as the users' computers. The purpose of the emulation is to allow testing and implementation of the VERTIGO system without the use of the actual Avionics Stack, which significantly increases accessibility for first-time users who are learning and developing VERTIGO-based programs, such as the GSP and GPF (Goggles Program File). It uses Linux Ubuntu 10.04 with pre-installed OpenCV 2.3.1, GPF and test projects. However, it should be noted that there is a discrepancy between the actual and the emulation processing power, due to the difference between the emulation computer's hardware and the actual Avionics Stack processing power.

4.1.2.10 Financial Budget (AL)

VERTIGO was allotted \$450 for use in the development INSPECT. The VERTIGO budget is relatively small compared to the other subsystems due to the fact that the VERTIGO system is already whole and complete, and needs very little additional hardware or software support which would require a larger budget. The only expense during the development of INSPECT was the purchase of new SATA solid state hard drives to use for the VERTIGO Avionics Stack as main storage drives. Two SATA drives were required, but once purchased, it was found that one was faulty. A third drive purchased to replace the faulty drive.

Table 14: VERTIGO Financial Budget

Financial Budget:		\$450
Item	Cost (USD)	Notes
3 InnoLite SATADOM D150QV SATA drives	\$175 x 3	2 SATA drives needed; a third was purchased to replace a faulty original
Total Spent:	\$525	
Budget Remaining:	-17%	

4.1.3 Optical Rangefinder (MV, HS, MK, KH)

4.1.3.1 Driving Requirements and Relevance to INSPECT

The Optical Rangefinder (ORF) allows INSPECT to gather depth and near-infrared (~900 nm) images of its environment. This data is relevant to a number of potential guest scientist missions, such as:

1. Scanning an object in order to generate a 3D model, as a first step to inspecting that object.
2. Estimating the pose of SPHERES INSPECT relative to another satellite for docking purposes.
3. Navigating SPHERES INSPECT through an environment without the SPHERES Metrology system, using a Simultaneous Localization and Mapping (SLAM) algorithm.

Table 15. Optical Rangefinder driving requirements

SEN-1	Field of View	All imaging sensors shall have a minimum field of view of 33 degrees by 33 degrees.	SX-1, SX-2	Expectation of 30 degree rotation per image sequence with 10% overlap	Testing
SEN-2	Target Distance	The system shall determine the distance to a target object accurate to within 10 cm with precision to 2 cm up to 7 meters away	SX-1, SX-2	Defines ranging limits	Testing
SEN-3	Visible Light Image	The system shall resolve a visible-light image of a 1cm per pixel resolution from 1 m	SX-1, SX-2	Defines optical resolution limits.	Testing
SEN-4	Sensor Data	All sensors shall send data at a rate which can be processed by the VERTIGO computer or must include its own computer for data processing	SX-4	Need to transfer data	Testing
SEN-5	Thermal Image	The system shall resolve a thermal image of a 5x5 cm object from a distance of 1 m to +/- 5 degrees C accuracy and a noise equivalence temperature difference of <1 degree C at 20 degrees C.	SX-1, SX-2	Defines thermal resolution limits and accuracy/precision to produce a reasonable thermal image for our purposes.	Testing
SEN-6	Pose Sensors	The system shall be able to determine its pose in 2 dimensional space with 1 axis of rotation normal to the test floor	SX-1, SX-2, SX-5	Ability to support guest scientist navigation algorithms necessitates navigational sensors	Testing

4.1.3.2 Design Choice (MV)

The Optical Rangefinder selected for INSPECT is the MESA SR4000. The SR4000 is a phase shift time-of-flight camera. INSPECT will use the Ethernet data, wide field of view model of the SR4000. This choice was based on several factors, chief among them being the kind of data that the device could return (a 3-D point cloud without the need for gimbaling), lack of extra development effort needed to return a 3-D view, cost, and power requirements. The breakdown of this analysis may be found in Appendix B: Subsystem Tradespaces.



Figure 40: MESA SR4000 Phase-Shift Time-of-Flight Camera. [7]

The MESA SR4000 also provides data complementary to the VERTIGO system, since it can return much more accurate depth data than the VERTIGO stereo system can. These data can be brought together to form a 3-D map of the SPHERES's surrounding environment that is augmented by visual information from VERTIGO's cameras, which will form a useful set of information for both navigation and inspection.

For traceability to SPHERES-X, it should be noted that the MESA SR4000 cannot operate in sunlight. This means that this particular model will not work outside of the ISS. However, since INSPECT is designed for testing only inside ISS, this limitation will not pose an immediate issue. Additionally, Phase ToF cameras are limited to a maximum of approximately 20m (the SR4000 has a limit around 7m). This operational range will also not suffice for SPHERES-X. As such, SPHERES-X will not be able to use this class of sensor. That being said, the MESA SR4000 will output information in the same format as that produced by a LIDAR, so when an appropriate rangefinder is procured for SPHERES-X, the interfaces and data processing methods used by the SR4000 will transfer directly to the rangefinder used by SPHERES-X.

4.1.3.3 Mounting Structure (NC, MV)

Mounts were designed for both the MESA SR4000 and the FLIR A5. The mounts were designed to use the same components so that spare parts could easily be manufactured to fit either one. The major considerations that went into the mount design were fitting the required sensors and MICPCBs, weight, avoiding plume impingement, and ease of manufacture. For the MESA SR4000, an additional concern of thermal conductivity was considered, as the sensor tended to overheat if left on for extended periods of time.

To address these concerns, the mounts were designed to bring the sensors out of the plume impingement zone of the SPHERES thrusters. They were water-jetted from aluminum plates, with excess aluminum cut out when possible to reduce weight. (NC) Aluminum was chosen over plastic materials despite the slightly harder manufacturing process because aluminum is a better conductor and could be used to conduct heat away from the MESA SR4000 to extend its operating time.

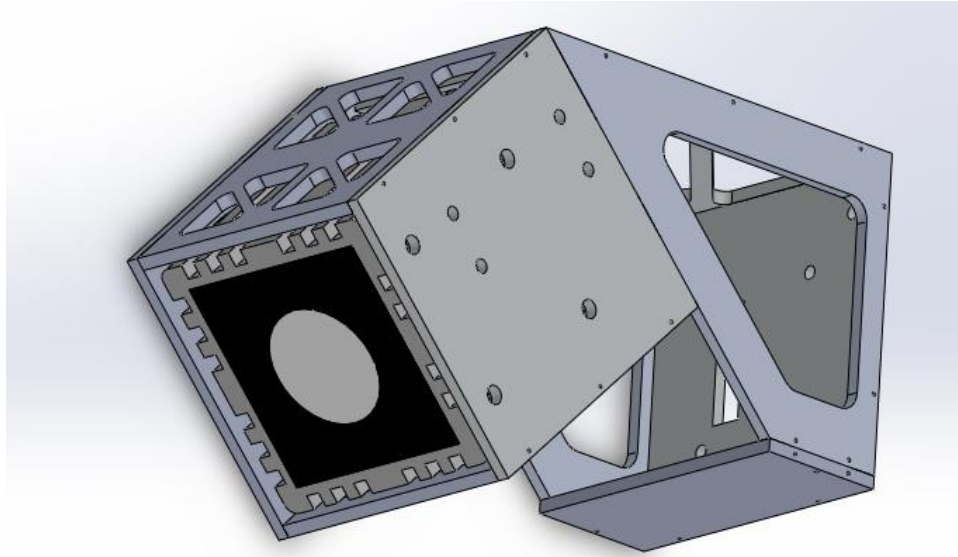


Figure 41 The CAD model for the sensor mount. Holes on the bottom plate allow for installation of the ORF. (NC)

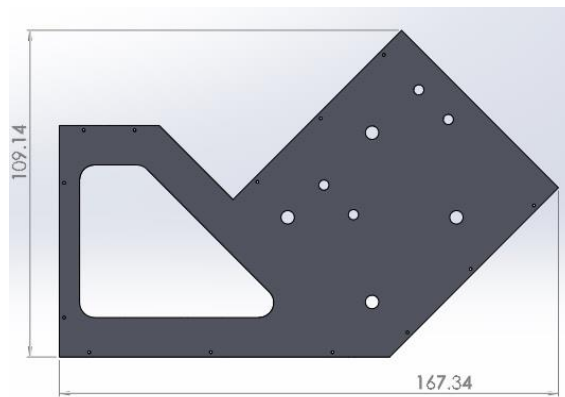


Figure 42 ORF Mounting Structure (dimensions in mm) (NC)

This mount connects to the Halo Port Footprint (Figure 31) via the outer set of inboard-to-outboard male mounting screws, which screw into female threaded holes on either the ThermoCam or ORF mount structure rear plate. The inner holes are used to secure the MICPCB in place so that the male 50 pin Samtec connector can make a secure connection with the corresponding female 50 pin Samtec connector on Halo. To ensure that the mount does not cause any electrical shorts on the MICPCB, the face adjacent to the MICPCB is covered in a layer of insulating kapton tape. (NC)

4.1.3.4 Power and Interfaces (KH, CK, JB, MV)

Table 16: Optical Rangefinder Peak Power Budget (JB, MV)

Peak Power Budget:		16.5W
Item	Power (W)	Notes
MESA SR4000	5.74	Measured
Regulator	0.78	Assuming 85% efficiency
Total Spent:	6.52	
Budget Remaining:	60.5%	

Table 17: Optical Rangefinder Average Power Budget (JB, MV)

Average Power Budget:		5.5W
Item	Power (W)	Notes
MESA SR4000	4.64	Measured
Regulator	0.63	Assuming 85% efficiency
Total Spent:	5.27	
Budget Remaining:	4.2%	

The MESA SR-4000 ORF requires 12V to operate, within a range of -2% to +10%, or 11.76V to 13.2V [7]. Halo provides 11.1V, which means that the MICPCB connecting Halo to the ORF requires a voltage regulator to step up the voltage to 12V for powering the ORF. Power is routed from Halo through the Samtec 50-pin male connector on the MICPCB. The Delta S24SE12002PDFA, a DC-DC power regulator with 9-36V input, 12V output and 20W was used in the MICPCB to step the voltage up to the 12V require by the ORF. While the health monitoring system discussed in section 4.1.1.6. was not implemented, the ORF was protected from any power surges by the Delta S24SE12002PDFA voltage regulator which was found out to reset the current draw to 0A if the current rose above about 1.5A.

The MICPCB which was integrated with the system to facilitate power delivery from the Halo to the ORF can be seen in Figure 35. The intended next version of the MICPCB, with health monitoring system, can be seen in Figure 31. (CK)

4.1.3.5 Data and Interfaces (CK)

As seen in the MICPCB Schematic (Figure 36) the ORF connects directly to the MICPCB to share data over Ethernet pins 1&2 and 3&6. The MICPCB then makes a direct connection between the Ethernet data links to the appropriate pins on the Samtec ERM8-025-09.0-S-DV-K-TR male 50-pin connector, which then relays the data to Halo via the ERF8-025-01-S-D-RA-TR female connector on the Halo Port #1. However, during integration and testing of the MICPCB in May 2014, the data capabilities of the board were not used, because Halo did not have working data connection on the ORF port. The ORF instead transmitted data through a central Ethernet switch that was connected into the VERTIGO dongle. See the Testing section below for more details. The intent is use the same Ethernet connector on the current MICPCBs in the future to route data through the MICPCB, after more testing. (CK)

4.1.3.5.1 Use of the 850 nm Spectrum

The use of the 850 nm infrared spectrum creates an interface issue between the ORF and the SPHERES US/IR Global Metrology system. The Metrology system is synchronized and activated by pulses of infrared light emitted by the master SPHERES satellite. When the Metrology beacons receive an IR pulse, they respond with an ultrasound pulse [8]. The SPHERES satellites have several receivers for both the IR and ultrasound pulses. The SPHERES satellites measure the time between their receipt of the IR pulse and the receipt of the ultrasound pulse from each beacon [8]. This time multiplied by the speed of sound gives the distance from each beacon to each receiver on the SPHERES satellite. The Metrology system software uses these distance readings to determine the position and orientation of the SPHERES satellite relative to the world-frame in which the beacons are set [8]. (MV)

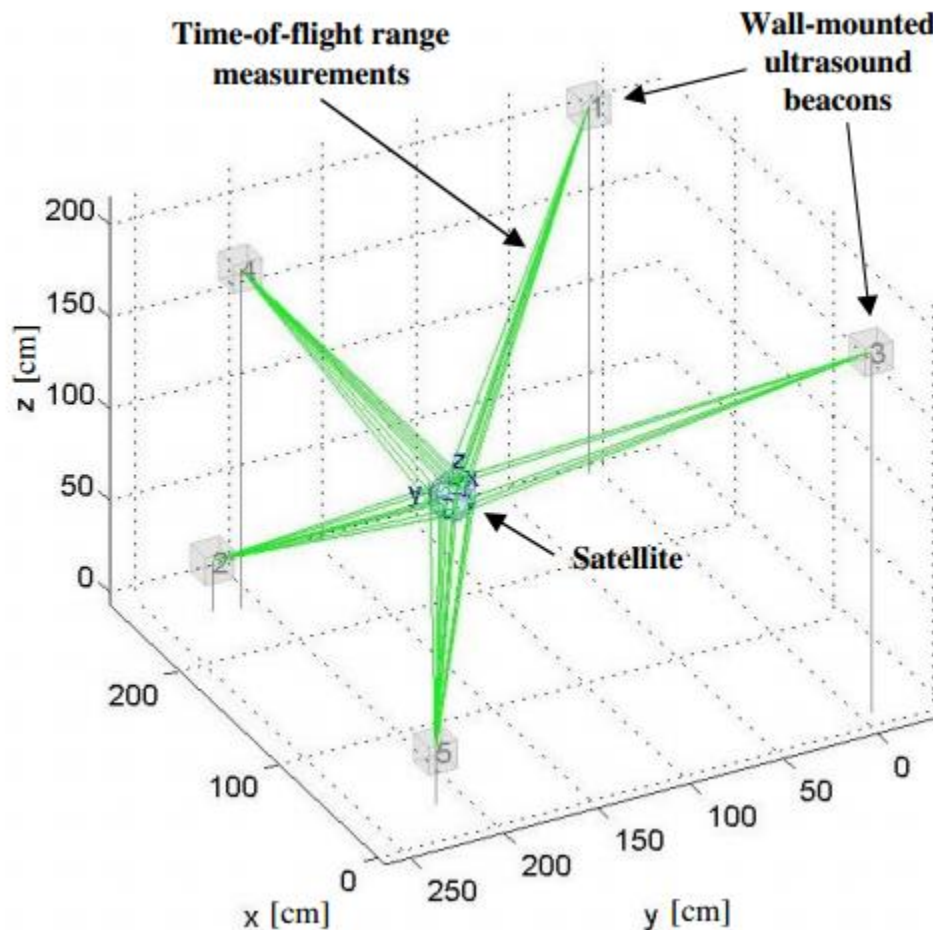


Figure 43: The SPHERES Metrology system uses time-of-flight measurements from ultrasound beacons to the SPHERES satellite [9].

The IR light emitted by the ORF triggers the IR receivers in the beacons and on the SPHERES [10]. If the ORF is operated sporadically, these IR pulses can cause the beacons to send out ultrasound responses which are out-of-sync with the Metrology system cycle. These extraneous ultrasound pulses can cause erroneous distance readings which degrade the accuracy of the Metrology systems position and attitude determination. The Metrology readings are passed through a nonlinear Kalman filter before being used to determine the satellite's pose, so some level of noise in the readings can be tolerated [8]. (MV)

If the ORF is operated continuously, and its light illuminates a SPHERES satellite (for example if one SPHERES satellite equipped with INSPECT is scanning another SPHERES satellite), the illuminated satellite can cease to function [10]. The highest-priority interrupt in the SPHERES Digital Signal Processor (DSP) software is the IR_Rcv interrupt, which is triggered whenever the SPHERES IR receivers detect IR light above a threshold intensity. If the SPHERES satellite is constantly illuminated with IR light, the IR_Rcv interrupt will be triggered so rapidly that other processes on the DSP will be starved of processor time. Particularly, the Fast_Housekeeping timer-based interrupt will be blocked from executing [see Figure 44]. If the Fast_Housekeeping tasks are not performed at the nominal interval, a watchdog process will reset the DSP [8]. When a SPHERES satellite is continuously illuminated with IR light, the IR_Rcv interrupt starves the Fast_Housekeeping, and the SPHERES resets its DSP over and over again without performing any useful computation [11] [10]. (MV)

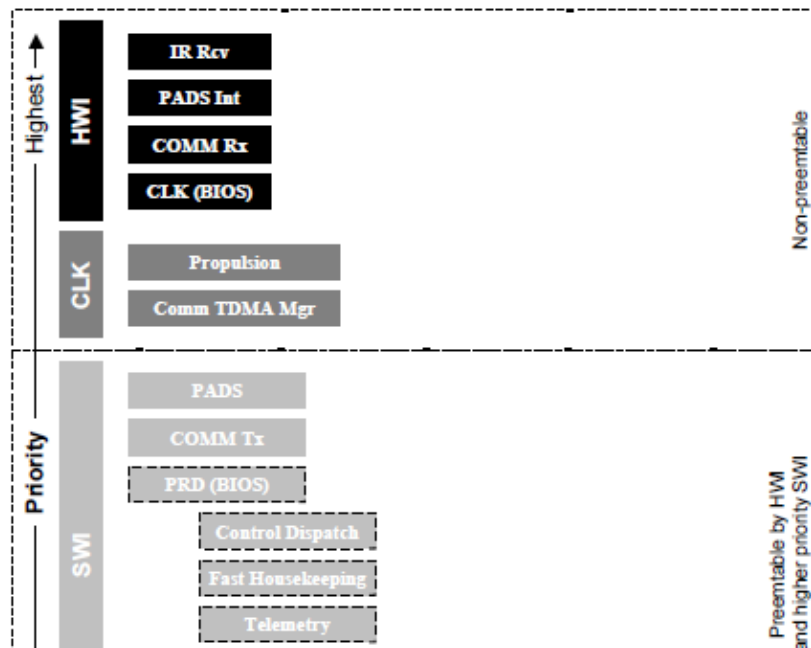


Figure 44: The highest-priority interrupts in the SPHERES DSP software architecture [8].

Even if the ORF is not illuminating a SPHERES satellite, the constant operation of the ORF severely degrades the accuracy of the Metrology system [see Figure 45]. Thus, the ORF cannot be operated in continuous acquisition mode when used in INSPECT. (MV)

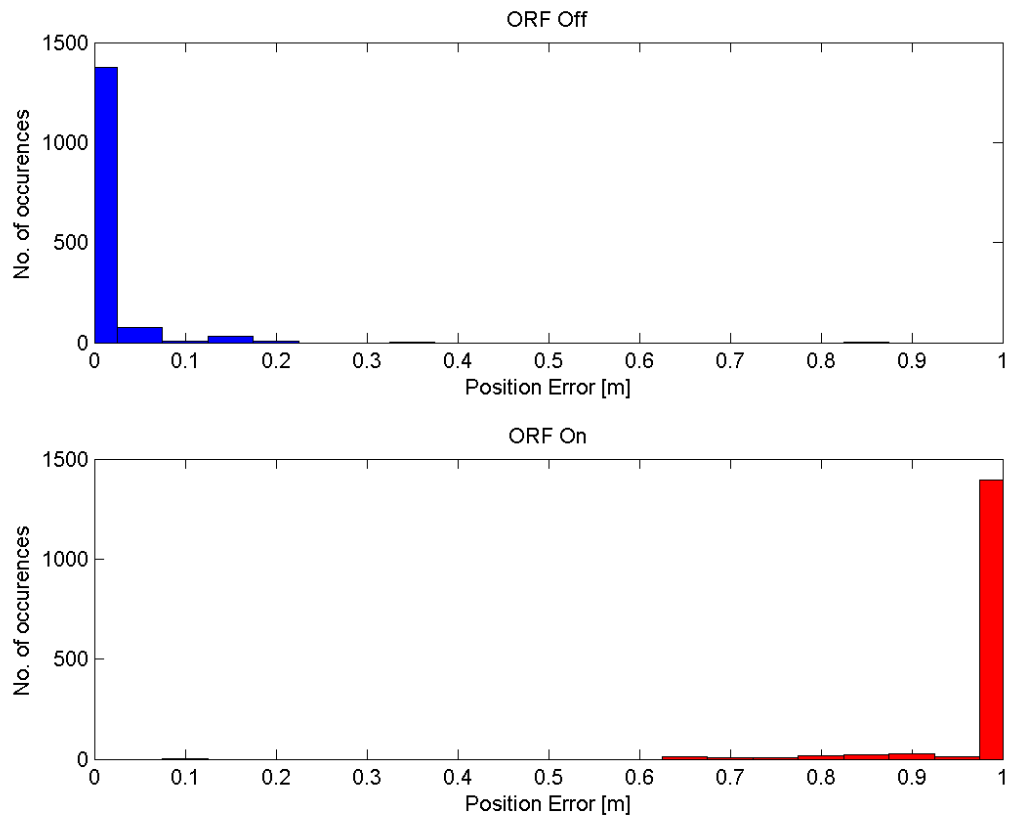


Figure 45: The distribution of position error samples measured with the ORF operating continuously [10].

At the nominal INSPECT imaging rate of 1 Hz, the ORF operation caused the positioning error of the Metrology system to increase to 140% of its normal level [see Figure 46]. This error increase is sufficiently low to allow the operation of the ORF in conjunction with the Metrology system in INSPECT.

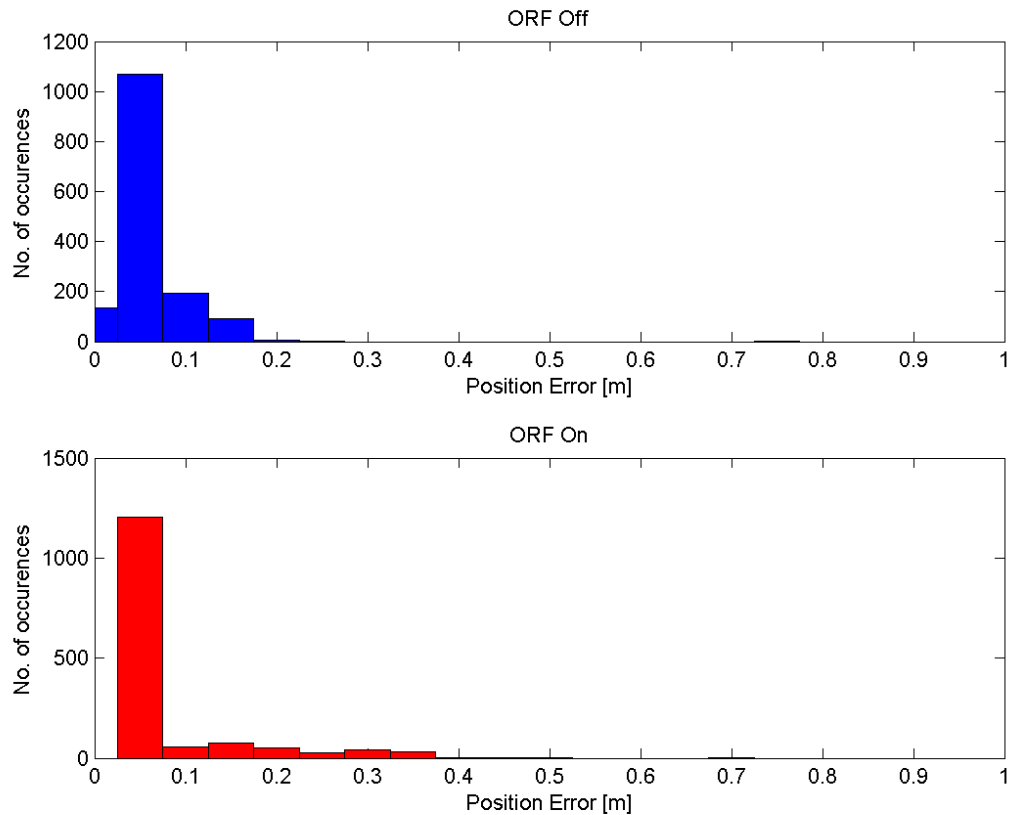


Figure 46: The distribution of position error samples measured with the ORF powering its lights for approximately 5 ms every 1000 ms [10].

Future researchers may wish to reduce the position and attitude determination error induced by the ORF. In order to do so, it will be necessary to synchronize the operation of the ORF's lights with the Metrology system, so that the Metrology system is shut down while the ORF is operation, and vice versa. Two options are presented for this synchronization: a message-based architecture and a timer-based architecture. In both architectures, the operation of the ORF can be caused to occur during thruster firings (when the Metrology system is already down) to minimize the Metrology down-time. (MV)

In the message-based architecture, message passing is used to ensure that the Metrology system is turned off before the ORF operates. The VERTIGO Avionics stack sends a `DISABLE_METROL` message to the SPHERES DSP, and waits for a `METROL_OFF` reply before operating the ORF. After the ORF is finished, the VERTIGO Avionics Stack sends an `ENABLE_METROL` message to the DSP so that it can reactivate the Metrology system. A limited and poorly documented message passing infrastructure exists between VERTIGO and SPHERES, and could be extended to implement this architecture. In order to improve the resilience to dropped messages, it may be desirable for the messages to be sent repeatedly until a response is received, rather than sent once. (MV)

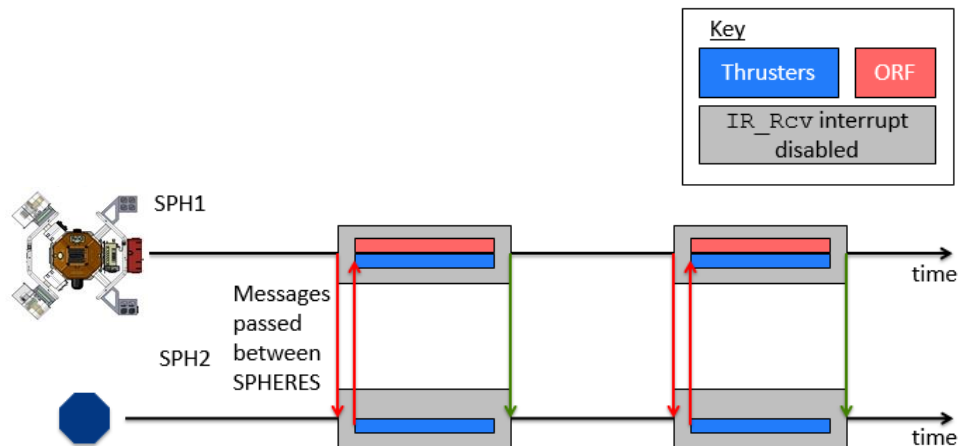


Figure 47: Message based synchronization of the ORF and the Metrology system (MV).

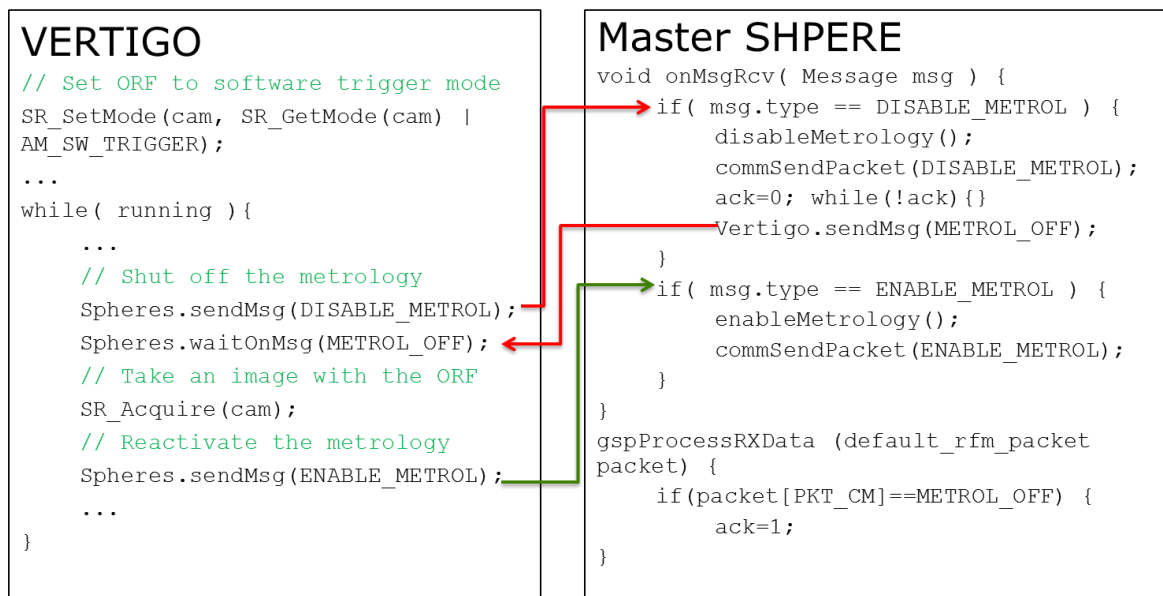


Figure 48: pseudocode for the message-based architecture. (MV)

In the timer-based architecture, the SPHERES DPS and VERTIGO track the time since the test start in their internal clocks. At fixed time intervals the VERTIGO stack operates the ORF and the DSP shuts down the Metrology system. (MV)

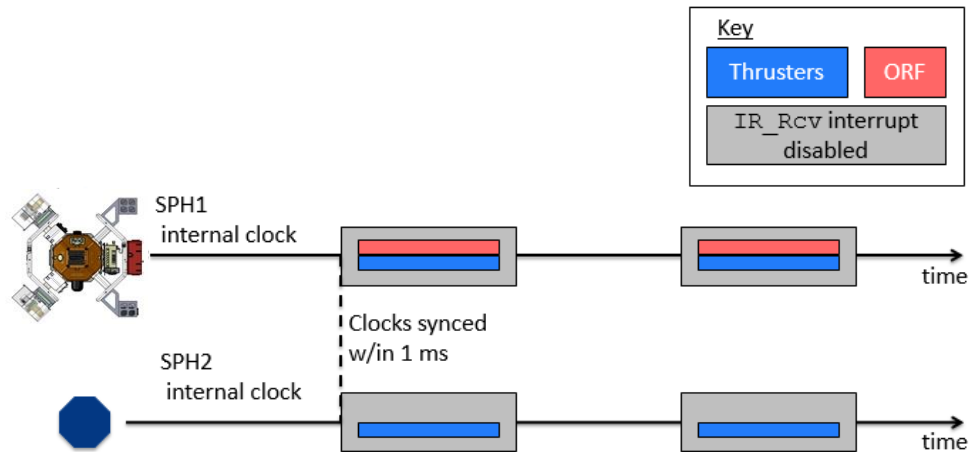


Figure 49: Timer based synchronization of the ORF and the Metrology system (MV).

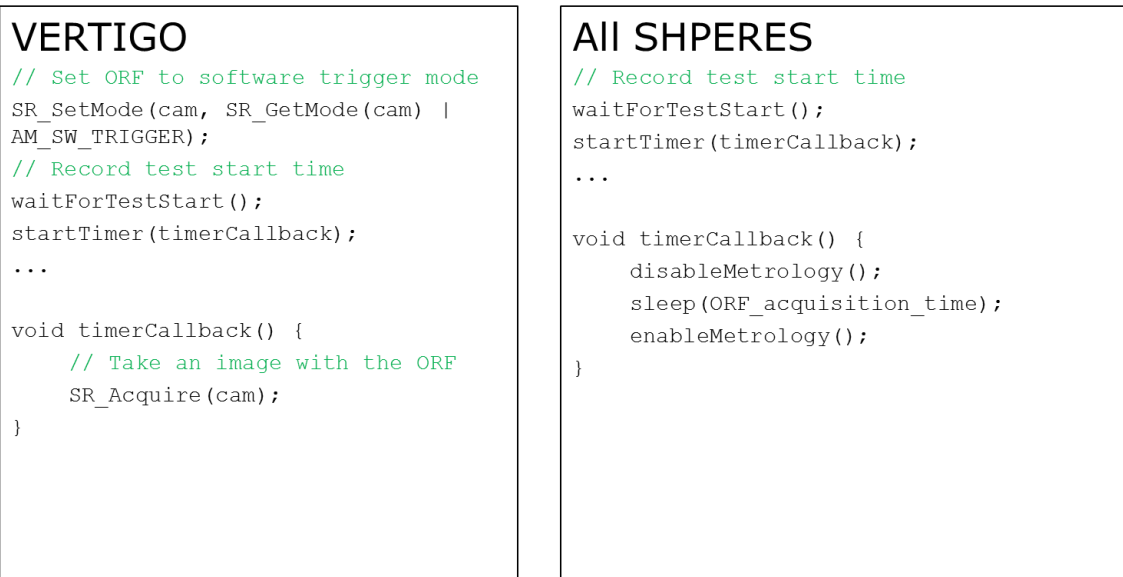


Figure 50: pseudocode for the timer-based architecture. (MV)

The time-based architecture is somewhat simpler to implement. However, it requires a rigid imaging schedule and can cause the Metrology system to be down for longer than needed. Further, the timers will interrupt other processes, possibly causing the delay of critical work. Also, during long missions the timers may drift out of sync. (MV)

The message-based architecture allows the INSPECT software running on VERTIGO Avionics Stack to dictate a flexible imaging schedule. This may be desirable if a mission wants to increase the imaging rate when it comes across an interesting feature. Further the message-based system will not drift out of sync and will likely be much more reliable. Therefore the message-based architecture is highly recommended over the timer-based architecture. (MV)

4.1.3.6 Software (KH)

MESA provides driver software for the Ubuntu Linux operating system which will be used to communicate with the optical rangefinder from the VERTIGO Avionics Computer. As displayed in Figure 45, commands are sent from the VERTIGO avionics stack command port to the ORF. The ORF is commanded by the VERTIGO Avionics Computer to take and transmit distance

measurements at a rate of 1 Hz to the VERTIGO Avionics Computer, where they are stored on the SSD via SATA in a format accessible by OpenCV, which involves creating a Mat object to store the image information of the data matrix including the matrix header and pointer. (KH)

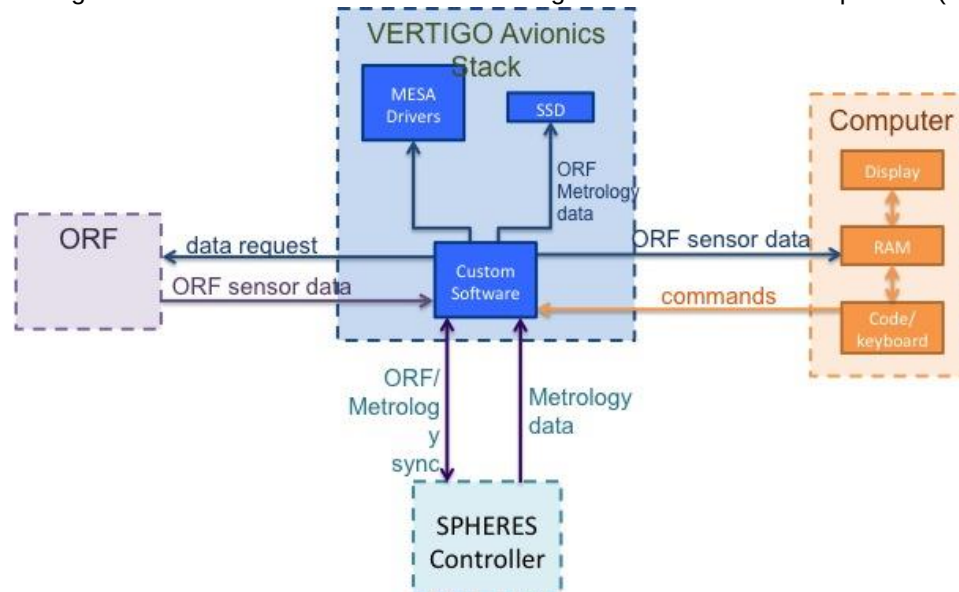


Figure 45: Software Interface Diagram

4.1.3.7 Mass (MV)

The MESA SR4000 has a mass of 0.510 kg. With mounting and interface devices, the total mass of the Optical Rangefinder subsystem on the Halo port will be 0.828 kg.

Table 18 Optical Rangefinder Mass Breakdown (MV, CK)

Mass Budget:		1.8 kg
Item	Mass (kg)	Notes
MESA SR400	0.510	The ORF, Measured
Mount	0.278	Structural Mount for ORF, Measured
MIC PCB Board	0.020	Approximate mass of finalized PCB, Estimate
Wiring	0.020	Approximate mass of all wiring to Halo/PCB, Estimate
Total Spent:	0.828	
Budget Remaining:	54.00%	

4.1.3.8 Financial Budget

The allotted budget was intended for spending on the chosen ORF, PCBs and populating components, wiring, and structural connections. The largest percent of the budget was spent on the actual sensor, which at \$4,065.05 made up 60.22% of the allotted budget. Other expenses included an appropriate power supply, connectors, PCBs, and components to test and then populate the PCBs. (CK)

Table 19: Optical Rangefinder Financial Budget (MV, CK, KH)

Budgeted:		\$6,750
Item	Cost (USD)	Notes
ORF Power Supply	39.78	Power Supply for ORF from DigiKey
ORF Power Connector	24.38	Power Supply Connector for ORF

PCB Breadboarding Components	133.38	Various components to test the PCB design on a breadboard
MESA SR4000	4065.05	The Optical Rangefinder sensor, MESA Imaging's Swiss Ranger 4000
PCB Surface Mount Components	84.93	MIC PCB Surface Mount Components
MIC PCBs	97.22	MIC PCBs
Ethernet Connector for PCB to ORF	14.79	Ethernet Connector to connect MIC PCB to the ORF
ORF Power Connector (for PCB to ORF tests)	24.38	Power Supply Connector for ORF for PCB to ORF testing
Total Spent:	4483.91	
Budget Remaining:	33.57%	

4.1.4 Thermographic Camera (KAF, TW, NC, CL, AW)

4.1.4.1 Driving Requirements and Relevance to INSPECT (KAF)

The thermographic camera (ThermoCam) allows INSPECT to take thermographic images of its environment and transfer these images to the VERTIGO Avionics Stack for processing, where the data can be analyzed to identify temperature extrema within the camera's field of view. The driving requirements for the ThermoCam are listed below in Table 20. Requirements SEN-1 and SEN-4 ensure that the system is consistent with the other subsystems included in the INSPECT suite, and requirement SEN-5 outlines the resolution limits desired for the thermographic images.

Table 20: Thermographic Camera Driving Requirements

SEN-1	Field of View	All imaging sensors shall have a minimum field of view of 33 degrees by 33 degrees.	SX-1, SX-2	Expectation of 30 degree rotation per image sequence with 10% overlap	Testing
SEN-2	Target Distance	The system shall determine the distance to a target object accurate to within 10 cm with precision to 2 cm up to 10 meters away	SX-1, SX-2	Defines ranging limits	Testing
SEN-3	Visible Light Image	The system shall resolve a visible-light image of a 1cm per pixel resolution from 1 m	SX-1, SX-2	Defines optical resolution limits.	Testing
SEN-4	Sensor Data	All sensors shall send data at a rate which can be processed by the VERTIGO computer or must include its own computer for data processing	SX-4	Need to transfer data	Testing
SEN-5	Thermal Image	The system shall resolve a thermal image of a 5x5 cm object from a distance of 1 m to +/- 5 degrees C accuracy and a noise equivalence temperature difference of <1 degree C at 20 degrees C.	SX-1, SX-2	Defines thermal resolution limits and accuracy/precision to produce a reasonable thermal image for our purposes.	Testing
SEN-6	Pose Sensors	The system shall be able to determine its pose in 2	SX-1, SX-2,	Ability to support guest scientist navigation	Testing

		dimensional space with 1 axis of rotation normal to the test floor	SX-5	algorithms necessitates navigational sensors	
--	--	--	------	--	--

4.1.4.2 Design Choice (KAF, TW)

The thermographic camera chosen for the INSPECT system is the FLIR A5 micro-bolometer thermal imager. The FLIR A5 was chosen for its low volume and mass of 186.8 cm³ and 0.2 kg, respectively. This small size and mass make it ideal for inclusion on INSPECT. Additionally, the FLIR A5 was available to the team at a price of \$2205, and the 5 mm lens version provides a large field of view of 44° x 36° (horizontal by vertical, full-cone measurements). The FLIR A5 has a Power over Ethernet (PoE) connection that is capable of transmitting and receiving data as well as power over the same port. [12] For INSPECT, however, the PoE connection is not used, as the FLIR A5's use of Gigabit Ethernet necessitates the use of the Ethernet port exclusively for data transfer. The ThermoCam system will instead make use of the round M12 connector (visible in Figure 51 below) to provide power from the Halo port 5 to the FLIR A5. The full tradespace and tradespace analysis charts can be found in Appendix B section 11.2.



Figure 51: FLIR A5 Thermographic Camera [12]

4.1.4.3 Mounting Structure (NC, KAF)

Mounts were designed for both the MESA SR4000 and the FLIR A5. The mounts were designed to use the same components so that spare parts could easily be manufactured to fit either one, although the ThermoCam mount was later redesigned to extend out for an additional 1 cm. The decision to extend the mount was made in order to completely house the ThermoCam's lense within the mount structure and to provide ample room at the rear of the camera to comfortably insert the M12 I/O and RJ45 Ethernet connectors into their hubs. The major considerations that went into the mount design were fitting the required sensors and MICPCBs, weight, avoiding plume impingement, and ease of manufacture.

To address these concerns, the mounts were designed to bring the sensors out of the plume impingement zone of the SPHERES thrusters. They were water-jetted from aluminum plates, with excess aluminum cut out when possible to reduce weight. Aluminum was chosen over plastic materials despite the slightly harder manufacturing process because aluminum is a better conductor and can be used to act as a heat sink to conduct heat away from the FLIR A5, both extending the camera's operating time and preventing inaccurate temperature readings caused by overheating.

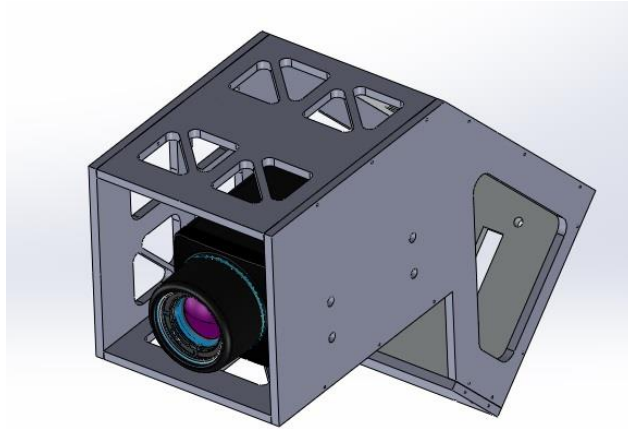


Figure 52 The CAD model for the sensor mount, with the Thermographic Camera in it for scale. Holes on the bottom plate allow for installation of the Thermographic Camera. (NC)

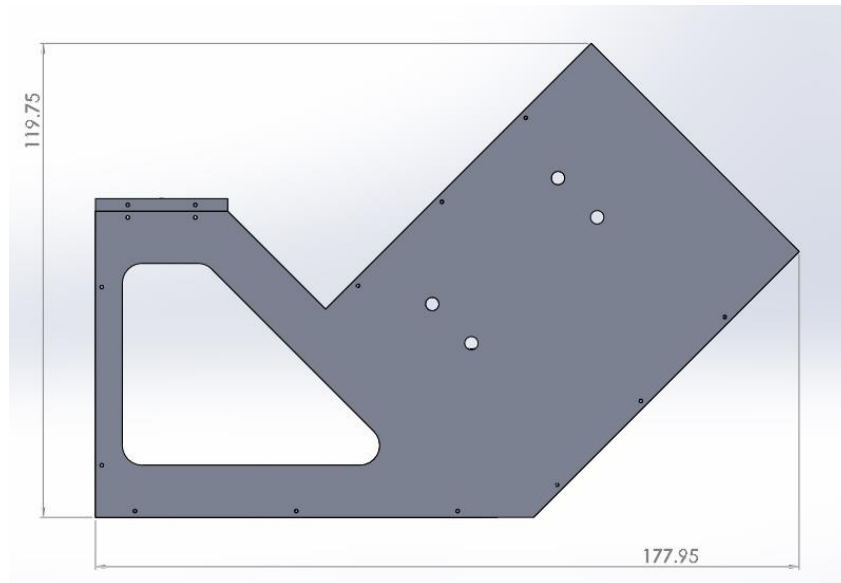


Figure 35: Thermographic Camera Mounting Structure (dimensions in mm) (NC)

The mount connects to the Halo Port Footprint (Figure 31) via the outer set of inboard-to-outboard male mounting screws, which screw into female threaded holes on the back plate of the mount structure. Three of the four inner holes are used to secure the MICPCB in place so that the male 50 pin Samtec connector on the board can make a secure connection with the corresponding female connector on Halo Port #5. To ensure that the mount does not cause any electrical shorts on the MICPCB, spacers and/or springs are placed between the heads of the screws and the Halo Port surface, shortening the length of thread that protrudes through the other side of the port and mount face. As an added protection, the face adjacent to the MICPCB is covered with a layer of insulating kapton tape so that the metal leads from the board's through-hole components do not come into contact with the aluminum surface of the mount.

4.1.4.4 Power and interfaces (CL, KAF)

The ThermoCam requires 12 V to operate, which it receives from Halo Port #5 through the Samtec 50-pin connector interface with the MICPCB. Halo provides 11.1 V unregulated to the Delta S24SE 12002PDFA, a DC-DC converter on the board, which steps up that voltage to the

required 12 V for the ThermoCam. The ThermoCam will be connected to the MICPCB via a 12-pole M12 connector (Figure 53 and Figure 54) that has been fitted with wires soldered to pins 1 and 2 only, for power and ground. The two wires will then connect from the M12 to the MICPCB through a 3-port screw terminal. The ThermoCam requires a minimum of 1.1 A (13.2 W) for start-up and pulls an average of 0.25 A (3 W) during steady-state operation.

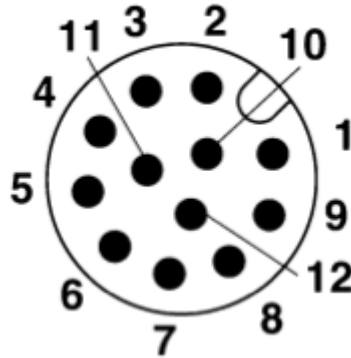


Figure 53: Pin assignment for M12 male connector, male side view (CL) [11]

Pin	Signal	Explanation
1	RET_GB	Camera PWR –
2	PWR_GB	Camera PWR +
3	SYNC_OUT	LVC Buffer @ 3.3 V, "0" = 24 mA max, "1" = –24 mA max.
4	SYNC_OUT_GND	= RET_GB = Camera PWR –
5	SYNC_IN	LVC Buffer @ 3.3 V, "0" < 0.8 V, "1" > 2.0 V
6	SYNC_IN_GND	= RET_GB = Camera PWR –
7	GPO+	1 × opto-isolated, 2–40 VDC, max. 185 mA
8	GPO–	= GP Input return
9	GPIO_PWR	GP Output PWR. 2–40 VDC, max. 200 mA
10	GPIO_GND	GP Output PWR return
11	GPI+	1 × opto-isolated, "0" < 2, "1" = 2–40 VDC
12	GPI–	GP Input return

Figure 54: Mapping pin to signal; only pins 1 and 2 are used with ThermoCam (CL) [11]

The MICPCB includes a simple health-monitoring system (as seen in the MICPCB layout in Figure 35: Multiple Interface Connection PCB (MIC PCB)) to give a visual indication if the PCB is not functioning correctly. As of testing in May 2014, the health-monitoring system remained untested due to manufacturing issues. A PPTC resettable fuse with a 1.1 A maximum holding current, a 1.95 A trip current, and a 300 millisecond trip time (Littlefuse 1812L110/16DR) is used in conjunction with an LED. The PPTC fuse will trip if the current being pulled through the fuse exceeds 1.95 A, and an LED light will turn on, indicating that all power must be cut and reset to the MICPCB in order to return functionality to the board and to the ThermoCam. The maximum current limit of 1.67 A on the input side of the voltage regulators will also protect the ThermoCam from being damaged from excessive current, as it will not be able to draw more than about 1.4 A of current (observed during MICPCB testing). The layout of the MICPCB is shown in Figure 35.

Table 21: Thermographic Camera Peak Power Breakdown (KAF)

Peak Power Budget:		16.5W
Item	Power (W)	Notes
FLIR A5	6	From Datasheet
Regulator	0.78	Assuming 85% efficiency
Total Spent:	6.78	
Budget Remaining:	58.9%	

Table 22: Thermographic Camera Average Power Breakdown (KAF)

Average Power Budget:		5.5W
Item	Power (W)	Notes
FLIR A5	3	From M12 Testing
Regulator	0.63	Assuming 85% efficiency
Total Spent:	3.63	
Budget Remaining:	34.0%	

4.1.4.5 Data and interfaces (CL, AW)

The ThermoCam uses Gigabit Ethernet to transmit data, meaning that all four twisted cable pairs in the Ethernet CAT6 cable are necessary for data transmission. The ThermoCam is connected to all eight pins of the RJ45 Ethernet port (pairs 1&2, 3&6, 4&5, 7&8) on the MICPCB, which in turn is connected to the appropriate data pins on the Samtec ERM8-025-09.0-S-DV-K-TR male 50-pin connector. The data is then relayed back to the VERTIGO Avionics Stack via the ERF8-025-01-S-D-RA-TR female connector on Halo Port #5. The ThermoCam sends 80 x 64 resolution images with a bit depth of either 8 bits per pixel or 14 bits per pixel at a maximum frequency of 60 Hz [6]. The data is transmitted as an array of unsigned int values with each value in the array representing the intensity value for a pixel. Via OpenCV, the intended image processing system for INSPECT, the data is stored in matrix form.

Table 23: Thermographic Camera Data Rate Breakdown (KAF)

Data Rate Budget:		512Mbps
	Rate (Mbps)	Notes
Total Spent:	2.46, 4.3	8 bits/pixel, 14 bits/pixel
Budget Remaining:	99.52%, 99.16%	

4.1.4.6 Software (AW)

The ThermoCam is compatible with GigE Vision protocol for data transfer via Ethernet and supports GenICam camera control protocol, which provides a generic API. The ThermoCam was be commanded by the VERTIGO Avionics Stack using the Pleora eBUS SDK 3.1.7, which is compliant with the ThermoCam's GigE Vision and GenICam standards. The Pleora eBUS SDK is available for the Linux Red Hat operating system but can be made compatible with the Linux Ubuntu operating system by linking appropriate libraries as outlined in the INSPECT Interface Controls Document. As displayed in Figure 55, via the Pleora eBUS SDK API, commands are sent from the VERTIGO Avionics Stack GigE Vision Control Protocol (GVCP) command port to the ThermoCam. ThermoCam data blocks are transmitted at a maximum rate of 60 Hz to the VERTIGO Avionics Stack and are received via the GigE Vision Streaming Protocol (GVSP)

streaming port. The eBUS Universal Pro Driver works to decrease the CPU utilization of the VERTIGO Avionics Stack as image data is received [13]. The data is then stored on the SSD via SATA in a format accessible by OpenCV, which involves creating a Mat object to store the image information of the data matrix, including the matrix header and pointer.

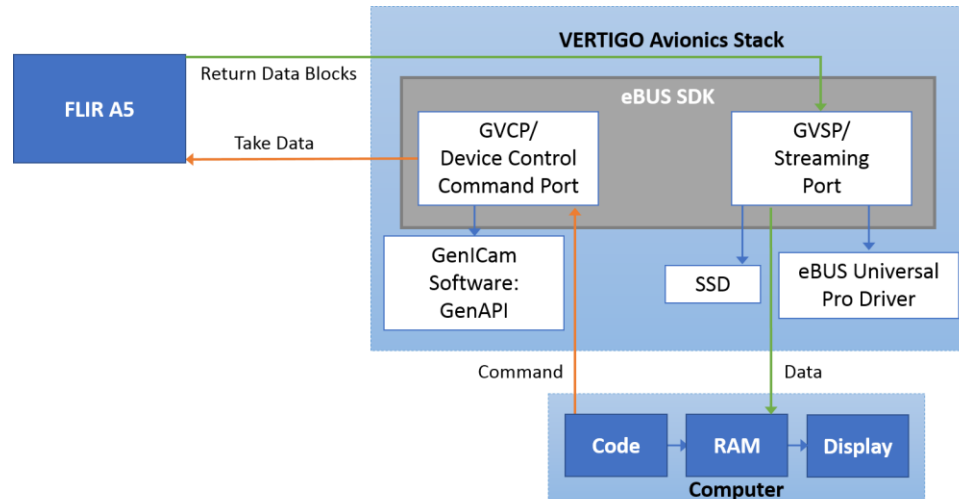


Figure 55 ThermoCam Software Flow Diagram

The ThermoCam software can be accessed via github, <https://github.com/awassen/INSPECT>, in the the “ThermoCam” folder. The main folder holds the ThermoCam Makefile and build script while a secondary folder containing a makefile and the main C++ code. Instructions for implementing the code are found in the INSPECT Interface Controls Document.

When the ThermoCam software is executed, the VERTIGO Avionics Stack is commanded to search for the ThermoCam and, if detected, to connect to it. The software then sends a command to open a stream between the VERTIGO Avionics Stack and the ThermoCam and populates the stream with buffers. At an image frequency specified in the ThermoCam software, each buffer is filled with one frame’s image data, consisting of an array of unsigned int values each representing an intensity value for one pixel in the frame. While the minimum image frequency to meet INSPECT requirements is 1Hz, the frequency can be changed following the guidelines in the INSPECT Interface Controls Document.

The image data is then transmitted to the VERTIGO Avionics Stack via the buffer in the stream. When the buffer reaches the stack streaming port, the image data is retrieved from the buffer. Using OpenCV, the raw data array for each image frame is stored as an 80 x 64 matrix, where each matrix element is a monochrome 8 bits unsigned int value for the corresponding pixel. OpenCV is also used to open a window on a personal laptop connected to the VERTIGO Avionics Stack via the VERTIGO dongle and display the live stream of images being transmitted to the stack. Each image is also stored on the VERTIGO SATA drive as a bitmap file. Every image and raw data file is saved with a time stamp to millisecond precision.

After the image data is retrieved from the buffer, the buffer is released and is free to acquire and transmit other image data blocks until the stream is commanded to close via key press. The image data can then manually be transferred from the VERTIGO Avionics Stack to a personal computer via Internet or flashdrive.

To conduct a temperature analysis of an image, the raw data had to be converted from a matrix of monochrome intensity values to one of temperature values. In order to determine the conversion factor, FLIR Tools+ software for Windows 7 was utilized. Thermal images recorded from the ThermoCam using FLIR Tools+ are stored with an associated temperature value in degrees C for each pixel. A color image taken with FLIR Tools+ was imported into and read in MATLAB, displaying the image data as a matrix of truecolor RGB values. Using MATLAB, the RGB matrix was converted to a matrix of grayscale intensity values. Through a pixel-by-pixel comparison of the thermal image acquired from FLIR Tools+ and the grayscale intensity version of the same image acquired through MATLAB analysis, a series of 15 pixel intensity values were mapped to their corresponding temperature values. Using this process, a linear relationship between the pixel temperature value in degrees C, T , and the pixel intensity value, I , was determined to be $T = 0.22 * I + 22.7$ ($R^2 = 0.93$).

The raw image data acquired by the VERTIGO Avionics Stack was imported into MATLAB. The data matrices of pixel intensity values were converted to matrices of pixel temperature values in degrees C using the above equation.

Moving forward, a rigorous analysis should be carried out in order to develop a more accurate process of converting pixel intensity values transmitted from the ThermoCam to temperature values.

4.1.4.7 Mass (KAF)

The mass budget for the ThermoCam system is outlined below in Table 24: Thermographic Camera Mass Breakdown. The largest contribution comes from the system mount. Other contributions come from the FLIR A5 camera and the MICPCB and wiring needed to interface the ThermoCam with Halo Port #5.

Table 24: Thermographic Camera Mass Breakdown

Mass Budget:		0.9kg
Item	Mass (kg)	Notes
FLIR A5	0.188	From Acceptance Test
Mount, MICPCB, & power cable	0.390	Measurement
Ethernet cable	0.088	Measurement
Total Spent:	0.666	
Budget Remaining:	74.00%	

4.1.4.8 Financial Budget (KAF, CL)

The financial budget for the ThermoCam system is outlined below in Table 25. The PCB components and MICPCB orders were combined orders for both the ThermoCam and ORF subsystems; the costs listed in the table are half of the total orders.

Table 25: Thermographic Camera Financial Budget

Financial Budget:		\$4050
Item	Cost (USD)	Notes
FLIR A5	2300	From FLIR Systems, Inc.
PCB Components 1	66.69	From DigiKey
PCB Components 2	42.465	From DigiKey

PCB Components 3	135.835	From DigiKey
PCB Switches	43.75	From Mouser
M12 Pigtail	138.00	From Omega Inc.
MICPCB Iteration 1	48.61	From Advanced Circuits
MICPCB Iteration 2	136.245	From Advanced Circuits
M12 Connector end	30.91	From DigiKey
Total Spent:	2942.505	
Budget Remaining:	72.65%	

4.1.5 ACDS: CMGs (RN, JK, MK, JS, NM, HS)

4.1.5.1 Driving Requirements and Relevance to INSPECT (RN, updated by JK)

Table 26: ADCS Driving Requirements

C-1	Sensor Stabilization	The system shall stabilize all sensors to have a blur coefficient of less than or equal to 1. Blur coefficient = $(t_{int}/\theta_{res})\omega$	SEN-1	Sensors must be sufficiently isolated from vibration in order to prevent blurring of image data	Testing
C-2	Translation	System shall be able to translate in a controlled manner through three dimensional space in a microgravity environment to 1 cm accuracy.	SX-1, SX-2	Translation is necessary for navigation.	Testing
C-3	Attitude	System shall be able to control its attitude through three dimensional space in a microgravity environment to 0.5 degree accuracy.	SX-1, SX-2	Attitude control is necessary for navigation.	Testing
C-4	Angular Velocity	System shall be capable of achieving an angular velocity below 0.58 rpm (in inspection mode) and below 9 rpm (in navigation mode).	SX-1, SX-2	Sensor blur requirements during inspection and SPHERES internal gyroscopes during navigation limit allowable angular velocity	Testing
C-5	Saturation	The system shall be able to track saturation levels at all times.	SX-1	Need to know when CMGs are approaching saturation to maintain command authority	Testing
A-1	Sensor Movement	The actuators shall provide movement for sensors that require motor functions.	C-1	Some sensors may require increased field of measurement.	Inspection
A-2	Torque	The system shall be capable of producing a torque of at least 11×10^{-3} Nm.	C-4	Based on SPHERES torque capability	Testing and Analysis
A-3	Linear Acceleration	The system shall be capable of linearly accelerating at 0.02 m/s^2	C-3	Allows for system translation	Testing

4.1.5.2 Design Choice (RN, MK, JK)

Honeybee's Low Earth Orbit LEO-H120-T50 Control Moment Gyroscopes were chosen as the ADCS for INSPECT.

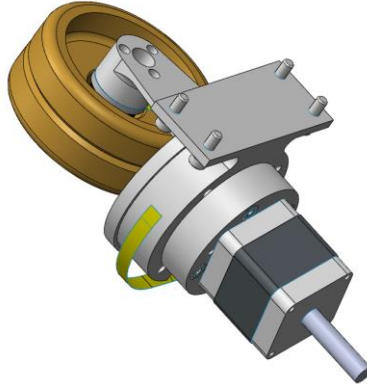


Figure 56: Honeybee LEO CMG

They each provide a maximum control authority of 0.16 Nm [14] of torque, which is higher than that provided by the SPHERES thrusters which can only provide a maximum torque of $(2 \text{ thrusters})(9.65 \text{ cm})(0.11 \text{ N}) = 0.021 \text{ Nm}$ about a single axis. CMGs provide a higher level of stability at a cost of roughly \$50k. The cost for the INSPECT CMGs will be covered by Draper Laboratories. 16.83x and 16.851 collaborated to generate a design that would meet the requirements for both projects. A trade study that aided in the elimination of other forms of attitude control can be found in 11.3 ADCS (LJ) in Appendix B.

4.1.5.3 Structures (JS)

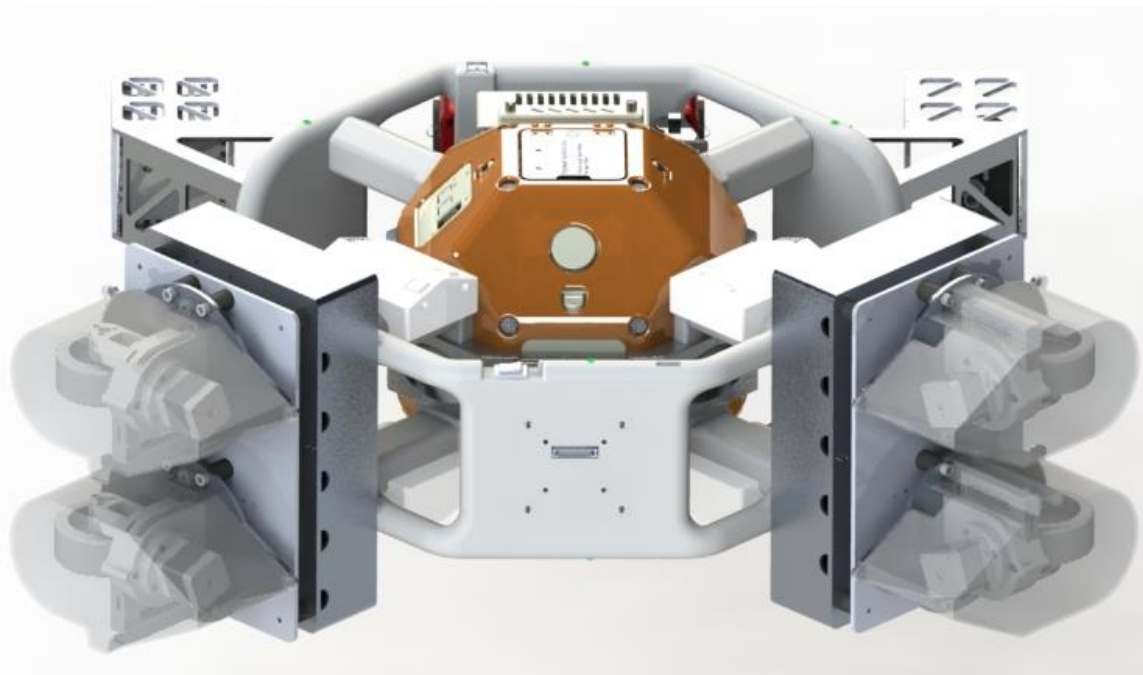


Figure 57: 16.851 CMG and Control Box Assembly [Box 90 Configuration]

The entire structural assembly for INSPECT's ADCS can be viewed in Figure 57. Given the CMG's inherent sensitivity and momentum generating capabilities, structural integrity, modularity, and vibrational dampening were the two dominating design factors for the CMG and CMG control-box mounting interfaces. From a high level, the CMG mounting design must allow each of two Halo ports to support two CMGs in both the Box-90 and Pyramidal configurations while completely enclosing the flywheel and gimbal for safety purposes; that is, four total CMG's, two on each port. Both of these ports will also be required to hold the drive electronics and PCB mounting assembly. While only one set of drive electronics is required, the redundant mounting assembly (which will be machined in order to match the specs of the one sent by HoneyBee) provides mass symmetry and ease of structural support. As a result, both pairs of CMGs will be mounted atop the control box sub assembly, separated by a 1/8 inch swivel plate and two sets of dampeners as pictured in Figure 58.

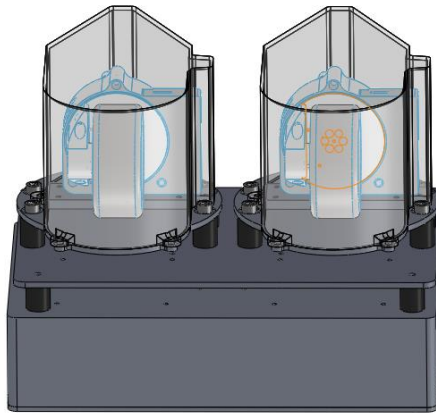


Figure 58: CMG Mounting Assembly

The CMG mounting assembly will allow two enclosed CMGs to swivel into either the box-90 or pyramidal configuration depending on user preference. The vibrational dampeners can be seen in Figure 58 as a barrier between the swivel plate and both the CMGs, and the control box itself. There are two total CMG mount assemblies. Each consists of the following structural components:

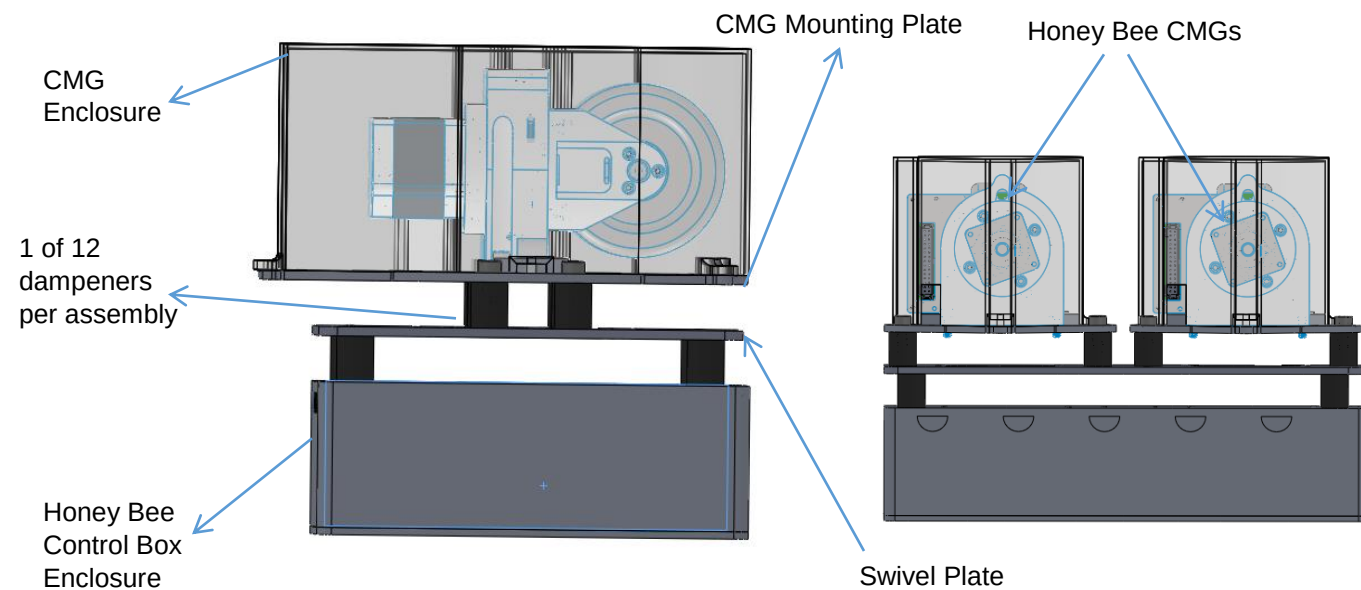


Figure 59: 16.851 CMG Mounting Assembly Components (Side and back views)

4.1.5.3.1 Honey Bee Control Box

Designed by Honey Bee, this is the main component to which all others will attach. It is the housing for the drive electronics. The hole pattern includes 4 threaded holes in a square pattern that will be the mechanical interface to attach to the swivel plate as seen in Figure 60: Honey Bee Control Box (Top View), along with 10, 0.136 mm holes and cylindrical standoffs to accommodate the CMG PCB hole footprint as shown in Figure 61.

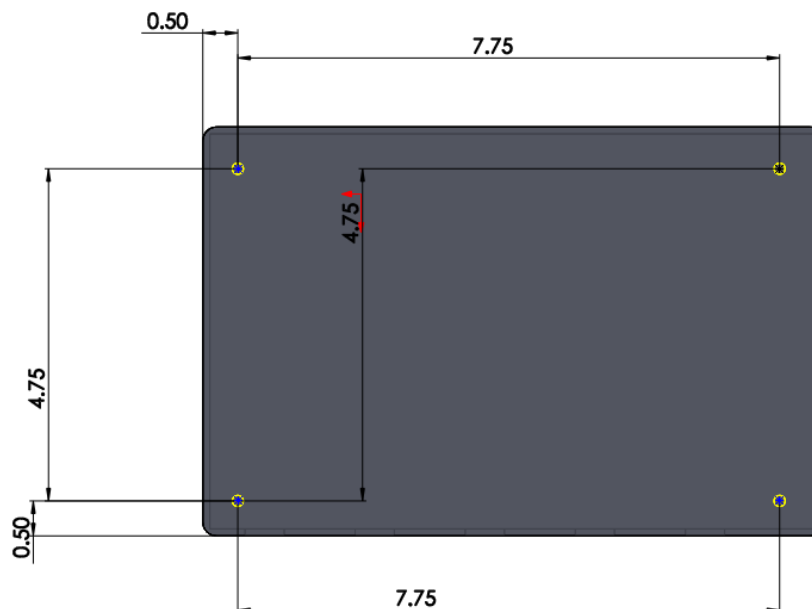


Figure 60: Honey Bee Control Box (Top View)

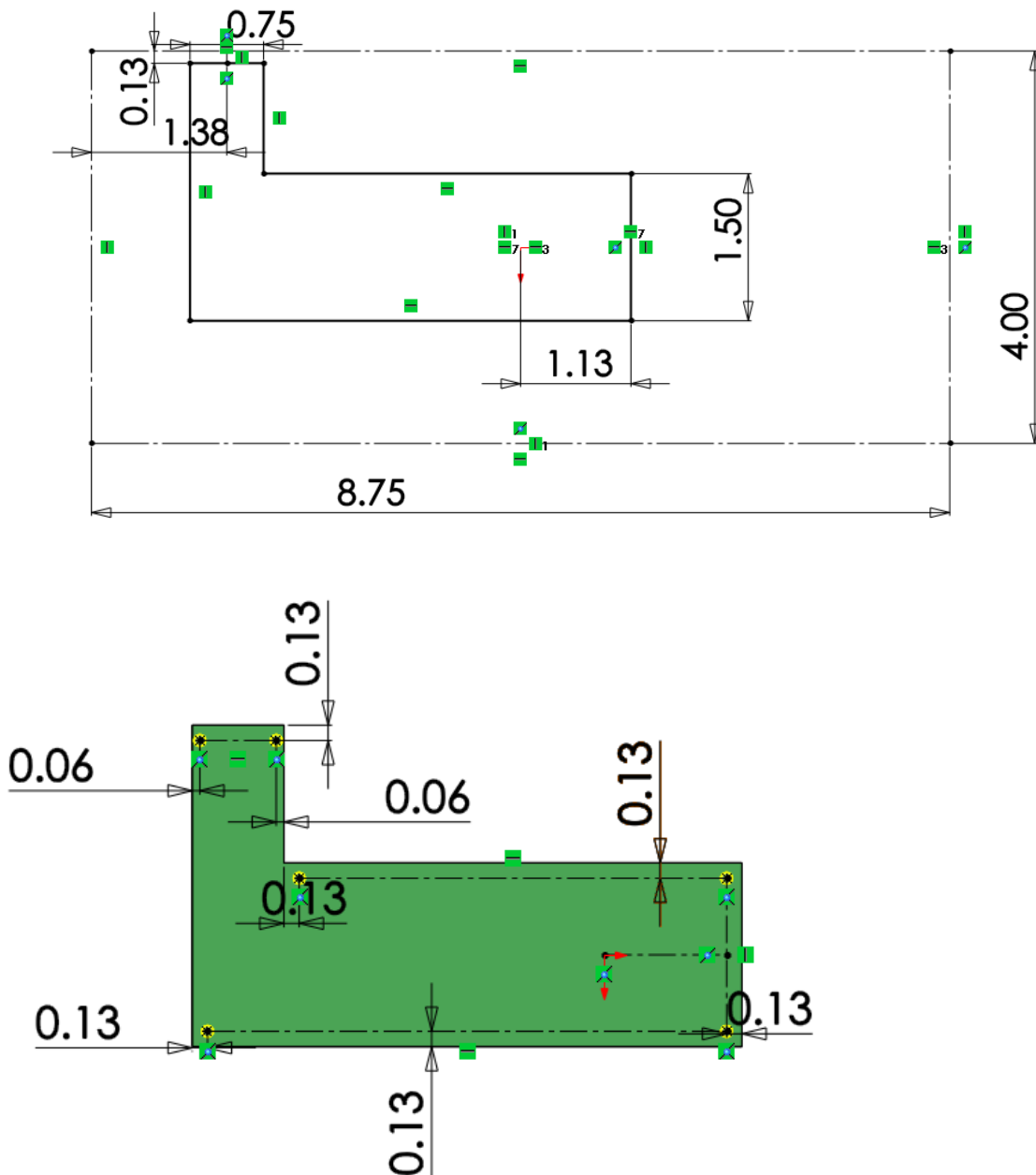


Figure 61: CMG PCB Dimensions and Hole Layout [in]

4.1.5.3.2 Swivel Mounting Plate

This is the plate to which the enclosed CMGs will directly attach. It contains 16 $\frac{7}{32}$ inch holes in a hexagonal pattern surrounding the large cut-outs for the CMG retainer. This is what will give the assembly the ability to accommodate both control configurations.

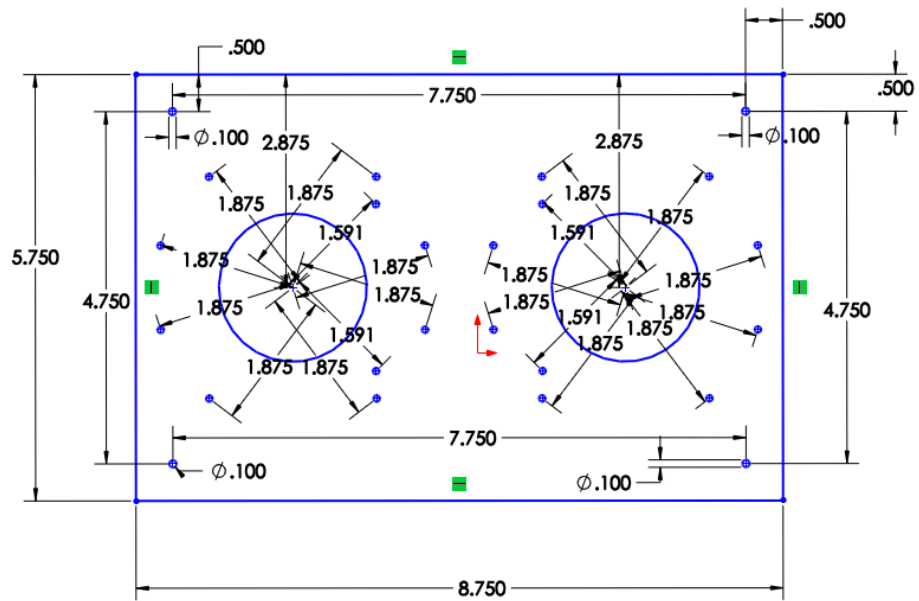


Figure 62: Swivel Mounting Plate

4.1.5.3.3 CMG Mounts with Captive Screws

The CMGs will be directly mounted on this component via 4 #6-32 tapped holes and screws. This component will attach directly to the swivel mounting plate via the 4 7/32" (for #4 socket) and captive screws and be constrained to the swivel plate plane by the CMG retainers.

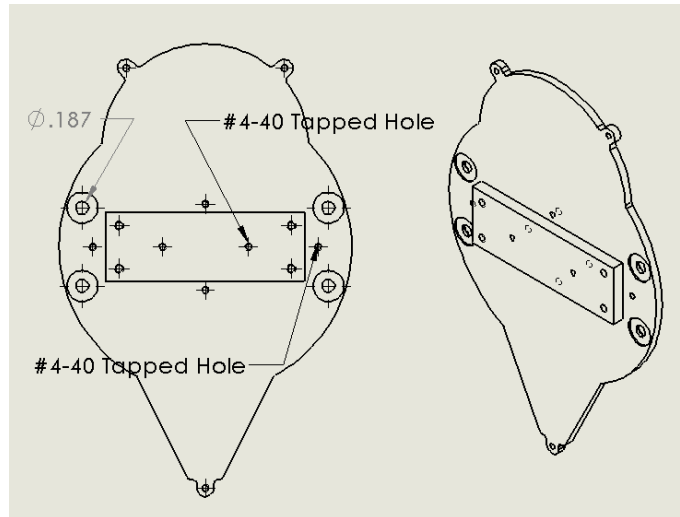


Figure 63: CMG Mounting Plate Drawing

4.1.5.3.4 CMG Covers (JS,JK)

Necessary for safety, this component will enclose the flywheel and gimbal while leaving a slit open for the RS-422 electrical interface. It will attach to the CMG mount via 4 #4-40 screws. For the purpose of 16.831, this component will be 3-D Printed according to the drawing in Figure 64: CMG Enclosure Drawing.

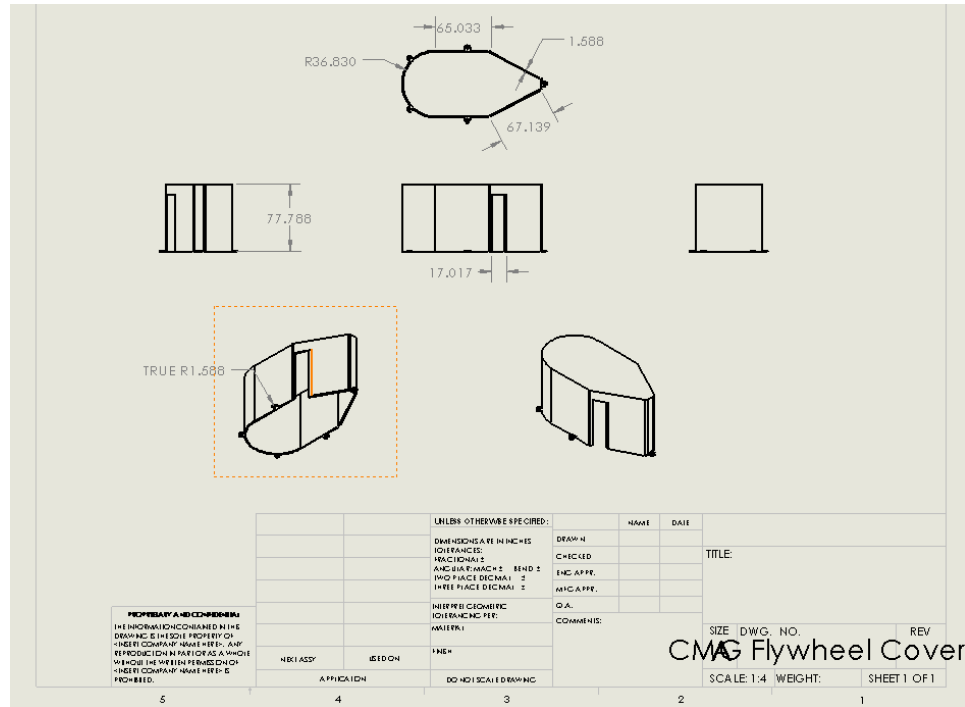


Figure 64: CMG Enclosure Drawing

The design was revised to include reinforced fasteners half an inch taller, as shown in Figure 59.

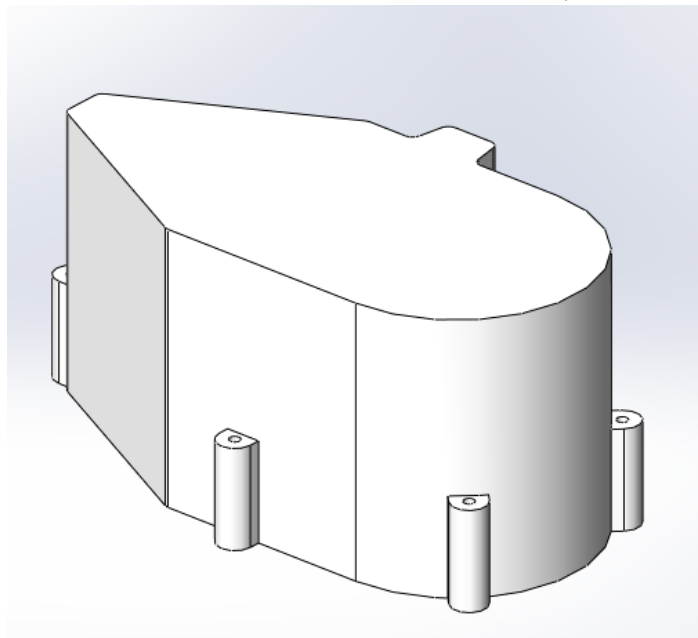


Figure 65: Reinforced Enclosure

4.1.5.3.5 CMG Retainers

This component, to be implemented after 18.83x, will allow for easy swivel ability and will bring redundancy into the design for safety purposes and structural integrity. It will fit in from underneath the Halo CMG interface plate and attach directly to the CMG mount via 4 #4-40

tapped holes and screws. The CMG retainer component will effectively secure the interface plate between the CMG mount and itself. This will allow for swiveling so long as the captive screws are not inserted and structural redundancy if they are inserted.

4.1.5.4 Power and Interfaces (JS, JK, MA)

The CMG subsystem requires 12V for normal operations. It receives power directly from Halo via the 50-pin Samtec connector, which provides 11.1V at 1.5A. The flow of power is as follows:

50 pin connector → CMG PCB → CMG Control Box → 20 pin micro d x 4 → CMGs x 4

The different states of the CMG payload will determine its power requirements at any given time. While spin-up of the flywheel was thought to require the most power, this is only the case if the gimbal motor is enabled. Otherwise, max power draw occurs when the CMGs are at max flywheel rate (6000 RPM) and max gimbal rate (60 deg/s). Spin-up occurs only once per normal operation. Therefore, the potential for an over maximum power draw can be eliminated with a sequential spin-up of each CMG with all gimbal motors disabled. Spin-up power draw under nominal conditions is higher than Halo allows, however two strategies can be used to bring that rate down to acceptable levels. First, the CMGs may be spun up sequentially instead of simultaneously, meaning that only one CMG is spinning up at a time. Second, each CMG can vary the rate at which it is spun up; decreasing that rate will proportionally increase the amount of time each spin-up takes. Using this strategy, power draw at spin-up can be lowered to acceptable levels. If spun-up sequentially, the CMGs will not cancel each other's' angular momentum, thus the system must be physically secured during spin-up.

Steady state is when the gimbal rates are zero, while peak is when gimbal rates are at their maximum.

Table 27: CMG Peak Power Breakdown

Peak Power Budget:		---W
Item	Power (W)	Notes
CMG	9	Occurs when all four CMGs at maximum torque
Regulator	3	
Total Spent:	12	
Budget Remaining:	4.65	

Table 28: CMG Average Power Breakdown

Average Power Budget:		---W
Item	Power (W)	Notes
CMG	5.7	
Regulator	3	
Total Spent:	8.7	
Budget Remaining:	-1.7	

Table 29: CMG power requirements [14]

Item and State	Power Required
4xCMGs + Drive Electronics Steady	7 watts
4xCMGs + Drive Electronics Peak	11 watts
4xCMGs + Drive Electronics Spin-Up	14 watts

4.1.5.5 Data and Interfaces (NM)

The CMG controller will interface with the 50-pin Samtec connector that is propagated to all of the Halo ports. The Honeybee control assembly attaches to one port and interfaces directly with four Honeybee LEO CMGs.

The LEO model requires RS-422 input, which is not available on the Samtec connector. In order to transfer data to and from the LEO model controller, an interface PCB is required to convert the USB signal to RS-422. A diagram depicting the overall data flow is shown below.

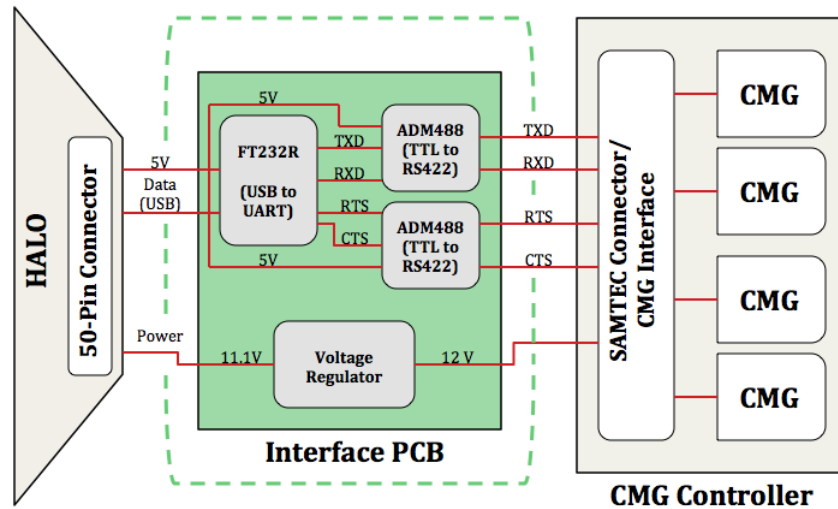


Figure 66: CMG PCB Board Flow Diagram (NM)

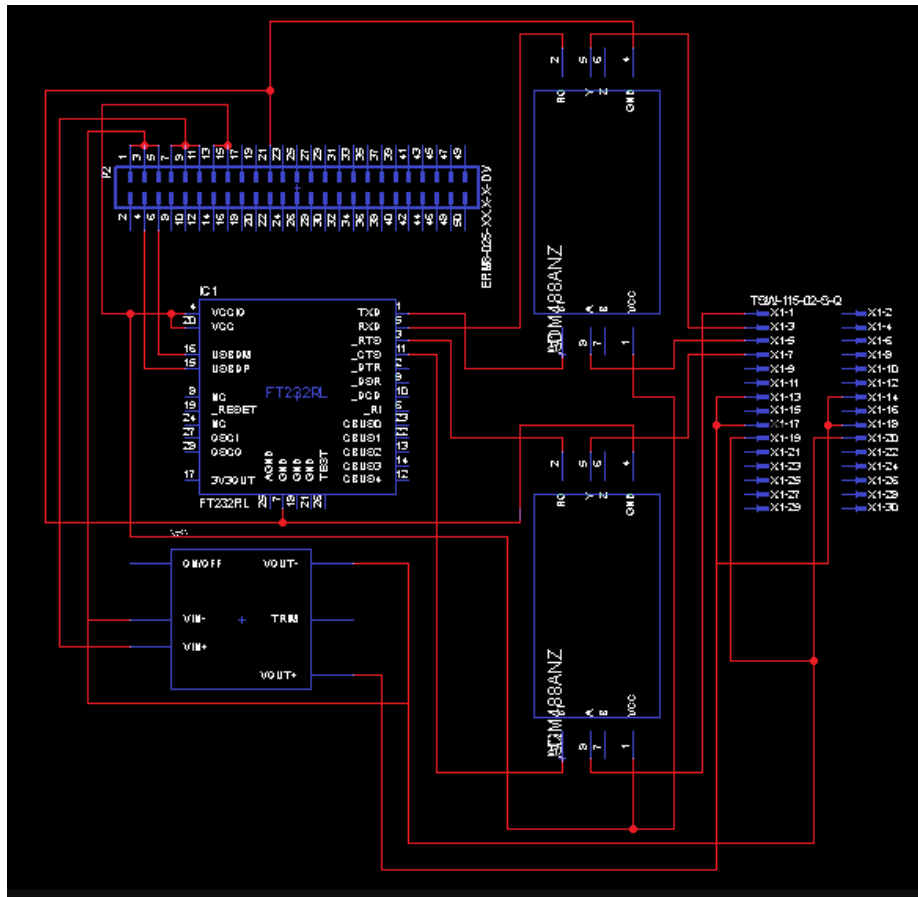


Figure 67: CMG PCB Schematic (NM, GP)

The PCB shown in Figure 67: CMG PCB Schematic (NM, GP) (outlined in Figure 66: CMG PCB Board Flow Diagram (NM)), works in a two-step process. It first converts the USB signals from Halo to UART/TTL and then from UART/TTL to RS 422. The first step uses a FT232R chip commercially available from FTDI Chip. It takes in the transmit and receive USB data lines and returns the same transmit and receive (TXD, RXD) as UART/TTL and well as a handshaking signal pair (RTS, CTS) as UART/TTL. The second step requires 2 ADM488 chips from Analog Devices. One chip converts the transmit and receive (TXD, RXD) UART/TTL signals to transmit and receive (TXD, RXD) in RS 422. The other chip converts the handshaking signals (RTS, CTS) from UART/TTL to RS 422.

In addition, the PCB draws two separate power sources from the Samtec 50-Pin connector. The 5V source is used to power the FT232R and ADM488 chips on the PCB itself, while the 11.1V source is fed directly to the CMG Controller Board for overall system power. The 11.1V source must be stepped up to 12V using a Delta S24SE12002PDFA DC-DC power regulator to meet the specifications of the CMGs. This is the same voltage regulator used in the ORF/Thermocam MICPCB. The PCB also includes all necessary grounding connections for system safety.

The allotted footprint of the PCB inside the CMG Halo Standoff Box is shown here in Figure 68. The PCB is aligned with the Samtec 50-Pin connector from the Halo port where it draws both data and power over USB. The thinner end of the PCB, which protrudes out towards the front of the assembly, is reserved for the electrical interface to the CMG Controller over RS 422 connections.

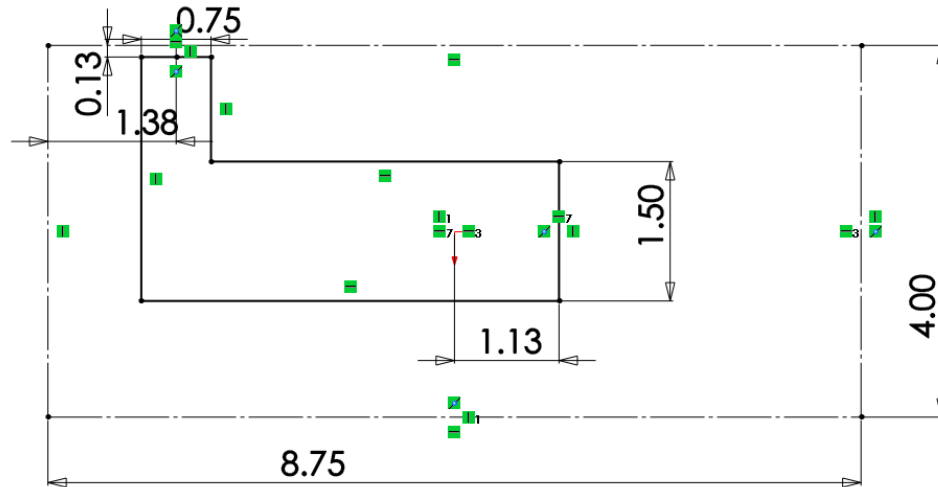


Figure 68: CMG PCB Footprint [in] (JS, NM)

4.1.5.6 Software Overview (AV, MA)

Software infrastructure for testing of CMG usage on SPHERES, both in MATLAB simulation and in the MIT Space Systems Laboratory hardware test bed, has been developed by 16.851 and 16.831. Figure 69 shows the software layout of SPHERES using CMGs for attitude control and thrusters for position control. Software was originally developed to control attitude in the z-axis of SPHERES, however it has now also been developed for rotation about the y-axis, which is the only rotational axis available in flat-floor testing inside the Space Systems Laboratory. This change in orientation was caused by the need to accommodate a CO₂ tank on the air carriage test structure. From the original SPHERES software, changes were made to the following.

- *Control Law:* Converts the state error into a set of force and thrust commands for SPHERES. A standard PD controller is used with modified gains for the CMGs. This control law outputs the necessary torques for a desired change in attitude.
- *Mixer:* Standard mixers convert forces and torques into thruster on/off times. A separate mixer to convert torques into either gimbal rates was developed. The torque values inputted from the CMG attitude controller are used to derive a necessary change in angular momentum about the y-axis by the CMGs. This change in angular momentum, together with the current gimbal position of each CMG in radians, can be used to calculate the necessary gimbal rate to result in the desired torque on the spacecraft. These gimbal rates are then sent to the Honeybee CMG Controller out of the UART port on SPHERES. Forces are still sent through the standard thruster mixer.

A Simulink model for the CMGs has been developed for use with the SPHERES simulation. The model has been tested in the 3 deg. of freedom case (x- and y-axis translation and z-axis rotation) by 16.851's CMG team.

Further development for software is necessary to extend the current systems to the 6 degrees of freedom case. This will require modifications to the CMG mixer as well as the Simulink model.

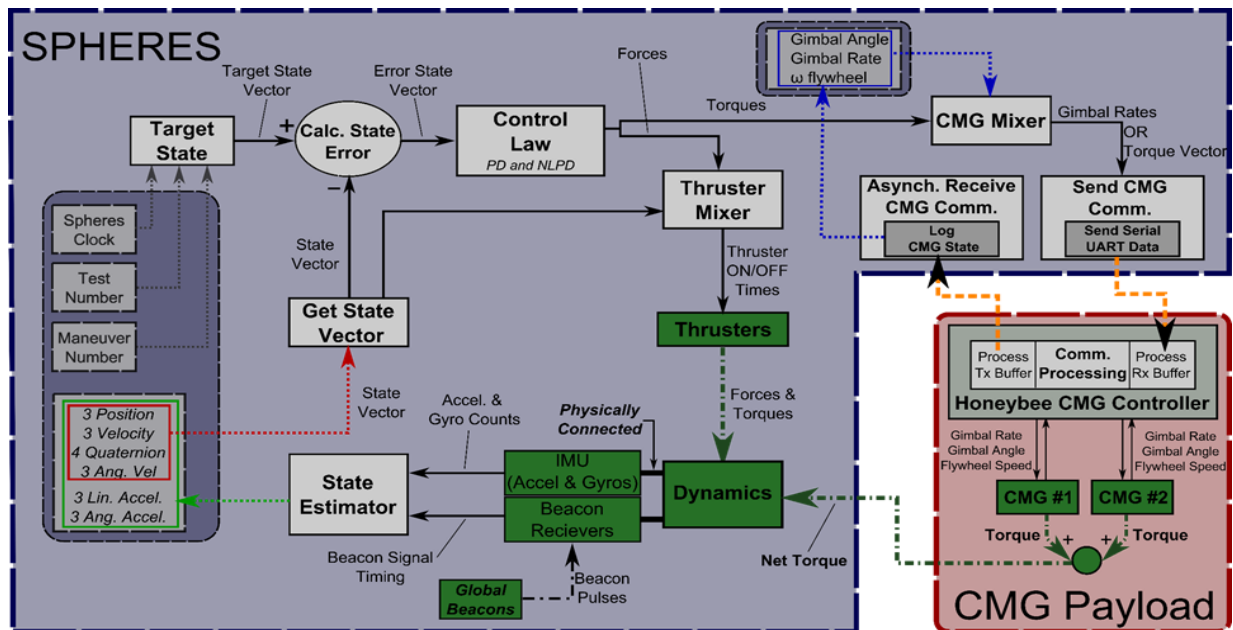


Figure 69: Block diagram of software system for SPHERES and CMG Payload

Onboard of SPHERES, the control algorithm collects the current state vector from the IMU and uses it to calculate the current error from the target state. With this information, the control law is then able to prescribe a desired torque on the satellite to be created by the CMGs. This torque is passed to the CMG Mixer where it is converted into gimbal rates for each of the CMGs. The current test configuration has this CMG mixer placed on VERTIGO, as communication between SPHERES and VERTIGO has yet to be accomplished. However, once this is the case, the CMG mixer could then be properly moved back onto SPHERES. In the single axis of rotation case, the four CMGs will act as scissor-pairs. This means that they will all change their gimbal positions to cancel all angular momentum components outside of the y-axis. The calculated gimbal rate is a non-linear function as it depends on the current gimbal position of each CMG. This data is requested from the Honeybee CMG Controller and returned to the GSP. Once the desired gimbal rate is calculated, it is then sent to the Honeybee CMG Controller through the UART port. This data packet passes from SPHERES through the VERTIGO Avionics Stack, though Halo, through the CMG PCB, and finally to the CMG Controller Board where it is implemented. Once this occurs, the inertial measurement unit updates the current state value of the system and the process is repeated.

4.1.5.7 VERTIGO-CMG Communications Software (HS)

A CMG control GUI was provided by Honeybee Robotics. The GUI runs exclusively on Windows, and is able to control CMG spin rates, gimbal rates, and gimbal positions via sliders. It can also take a slew of gimbal rates, which allows for an entire series of maneuvers to be specified at once. The code that underlies the GUI is also Windows-specific, which presents challenges in adapting the communications with the CMGs to VERTIGO's Linux system.

A low-level API was also provided by Honeybee [15], which specifies the bytes that must be sent over the CMG's serial connection to get status information and send commands to the CMGs. The message is built using a series of hexadecimal packets that all contain the following (in order): a message start section, a command type, a message body length, a message body, and a CRC checksum.

Two pieces of software were developed to support testing of the low-level communication. The first piece of software calculates the CRC checksum from a provided binary message, and verifies CRC checksums if a binary message is given along with its checksum. This is necessary because the checksum is determined by the message, and must be calculated rather than explicitly given by the Honeybee API.

The second piece of software is aimed at establishing serial communication between the CMGs and a computer programatically rather than through a GUI. Eventually this software will replace the GUI and provide an will serve as the core means of communication to and from the CMGs. Largely due to time constraints, this software is currently only able to demonstrate “liveness” of a connection, but not transmit any meaningful messages. (GP)

A communications software test plan was developed to safely test and integrate the CMGs with VERTIGO and eventually, SPHERES. However, this test plan was largely left unimplemented (except for the software development described above) by May 2014 due to time constraints.

4.1.5.8 Mass (JK, NM, MA)

The mass of the ADCS subsystem is divided among two Halo ports, each containing two CMGs with enclosures, swivel plates, standoffs, and the ribbon cable wiring to be run between HP2 and HP4. The PCB and control board will occupy a single port.

Table 30: CMG Mass Budget

Mass Budget:		6kg
Item	Mass (kg)	Notes
LEO H-120 CMGs	2.80	4 CMGs weighing 700 grams each
LEO Controller Board	0.50	1 Controller Board
Mounting Hardware	1.80	Estimated – Includes Standoff, Swivels, Screws, Etc.
Total Spent:	5.10	
Budget Remaining:	15%	

4.1.5.9 Financial Budget (JK, NM)

The CMG attitude control system was procured by Draper Laboratory for the 16.851 project, which then gave it to 16.83x. As a result, the CMG system itself (wheels + drive electronics) has no monetary cost to INSPECT. The CMG system has a value of over \$40k. Machined components are machined in the Aero-Astro machine shop and thus incur no monetary expense as well.

Table 31: CMG Financial Budget

Financial Budget:		\$3000
Item	Cost (USD)	Notes
TTL-to-RS422 Converter, 2x5-pin In, 4-Screw Out, for CoreWind	75.81	4 converters at 15.00 each, plus standard shipping
DLP-USB232M-G, Module USB to TTL SRL UART Converter	100.00	4 converters at 25.00 each, free shipping

Vibration-damping Mounts #9378K13	34.08	16 stiff vibration dampers at 2.13 each
Vibration-damping Mounts #9378K11	34.88	16 semi-stiff vibration dampers at 2.18 each
Vibration-damping Mounts #5822K4	36.00	4 flexible vibration dampers at 9.00 each
1-1/4" screws	6.61	For reinforced enclosures, one box of 100 screws
Total Spent:	287.38	
Budget Remaining:	89.4%	

4.2 Avionics and Communications

4.2.1 Data Interface (LJ, GP)

Figure 70 below displays the connection structure of the overall avionics and communications system.

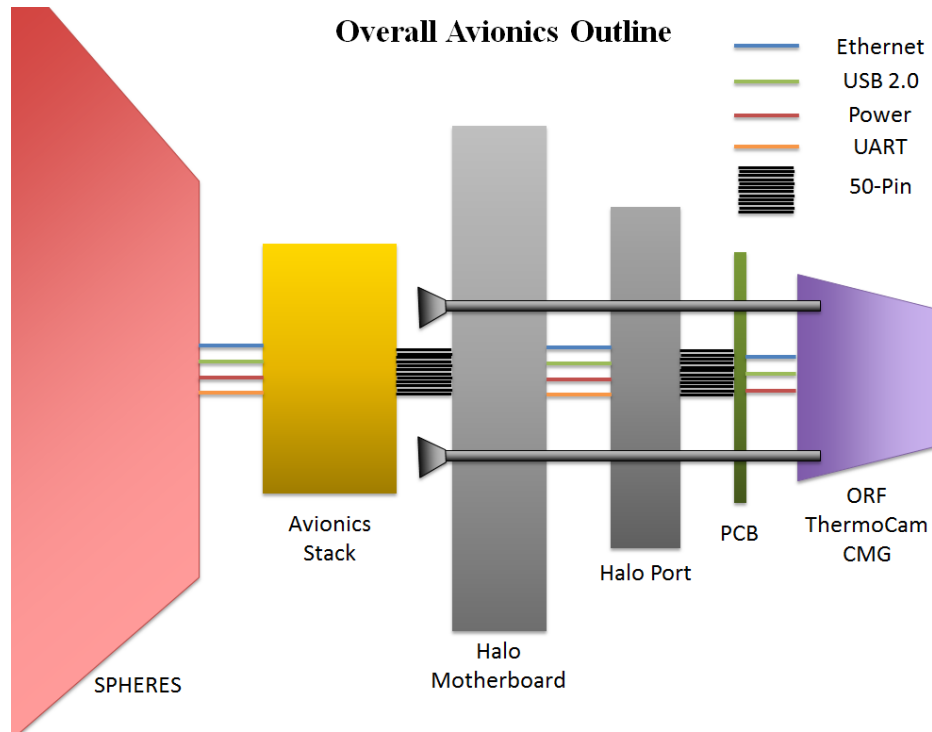


Figure 70: Avionics Outline (JB)

Table 32: Subsystem Processing Summary

Subsystem	FLOPS (10^6)	Processor Time (ms)	Allocated Processing Budget (ms)
Thermographic Camera	2.46	0.002	0.0022
ORF	40.55	0.034	0.0374
VERTIGO	10.83	0.009	0.0099
Actuators	240	200	220
Localisation Algorithm	360	300	330
Total	653.84	545	600

The Avionics Stack serves as the main hub, router, and central processor for all electrical signals and data for INSPECT. The 1.2 GHz Via Nano U3300 (Single Core, OOE, 1MB L2Cache) processor has 4GB of DDR3 RAM at 1066 MHz, two 64 GB Serial ATAs, and runs Ubuntu Linux 10.04. Data transport to and from the Avionics Stack is achieved through Cat 5 Ethernet, USB 2.0, and UART cables. All processes run on a 1Hz cycle rate.

[illegible]

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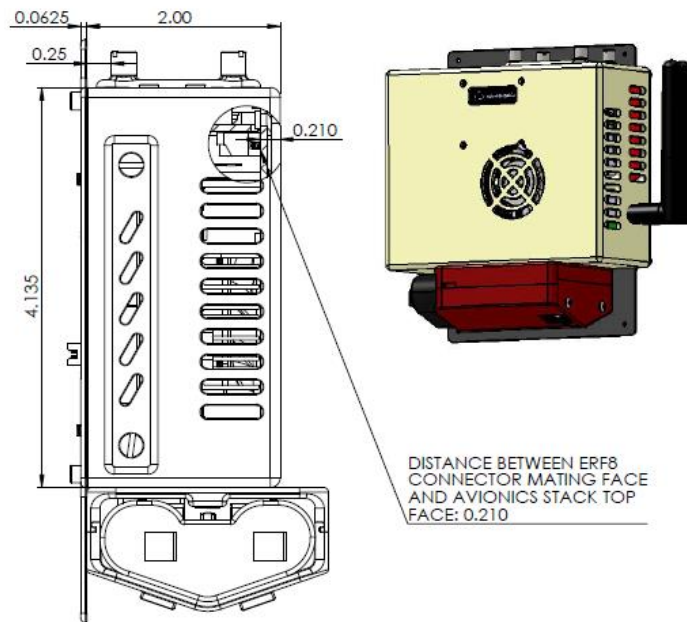


Figure 72 VERTIGO Avionics Stack - Side View

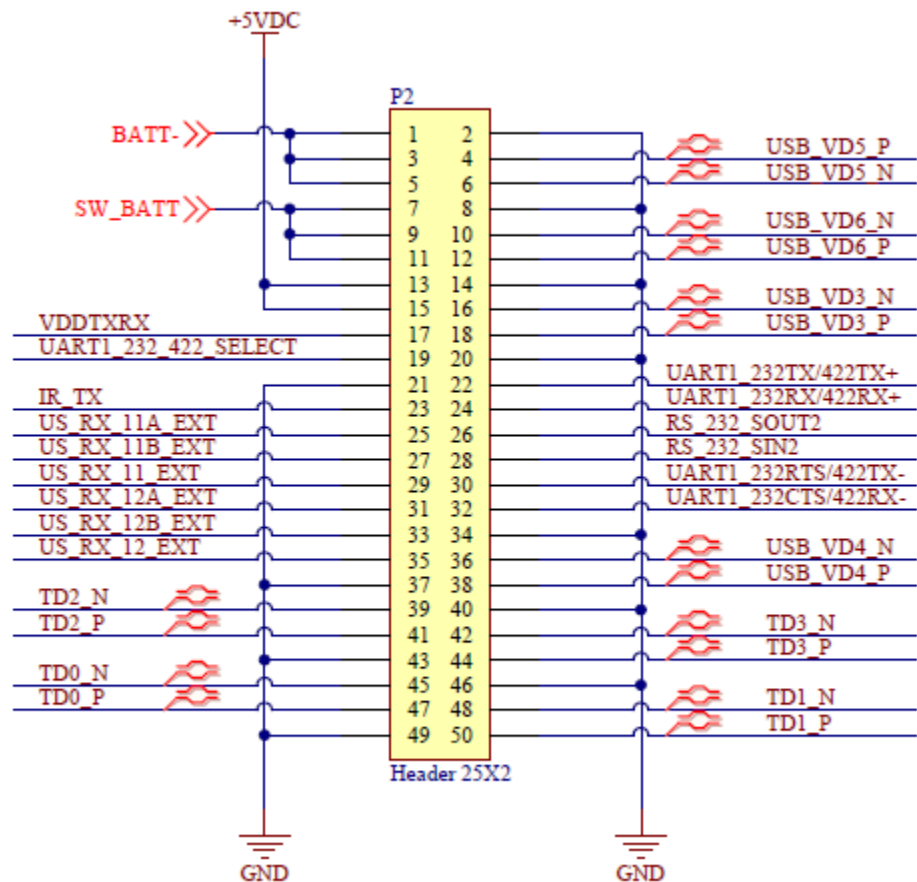


Figure 73: VERTIGO Avionics Stack Samtec 50-Pin Connector Pin Layout

4.2.2 Power Interface (JB, LJ, GP)

Halo can provide power to all of its 6 ports from its own battery packs. Battery packs each provide 11.1V unregulated (1.5A) or 5V regulated (0.5A). This gives 16.65 W of power total at each Halo port. A breakdown of the power distribution is included in 4.1.1.4. In the event that more than 1.5A of current is pulled from any Halo port, a PPTC fuse on Halo will trip, disconnecting the responsible Halo port from receiving further current until the port is switched off and back on. A similar response occurs when greater than 7.5A of total current is pulled from Halo's batteries: the entire system will trip a PPTC and will need to be entirely reset by the Halo master power switch. This maximum power limit levies an additional constraint on the system by preventing all peripherals from powering up at the same time to avoid tripping the total power fuse. This sequential power scheme extends also to individual CMGs, requiring that each CMG power on one at a time in order to not trip their own port, or the entire system as a whole. This is discussed in more detail in Section 4.1.5.4. All peripherals may run simultaneously operating on their average power budgets without concern of exceeding them.

4.2.3 Power Requirements

The processor power requirements are shown in Table 3: Power Budget Allocation and Table 33: Power Requirements for Avionics Processor Box . A 10% regulator inefficiency has been added as discussed in Dr. Brent Twedde's thesis [6].

Table 33: Power Requirements for Avionics Processor Box [6]

Components	Minimum (W)	Typical (W)	Maximum (W)
Pico-ITX P830	10.5	13	17.7
Flash Drives	1.25	1.25	3.4
Miscellaneous Items and Margin	0.5	0.5	0.75
Components Total	12.25	14.75	21.85
10% Regulator Inefficiency	1.225	1.475	2.185
Grand Total	13.475	16.225	24.035

4.2.4 SPHERES – On-Board Processing (MA)

In order to run the CMG control loops in real-time, the SPHERES CPU will be used to run the CMG control loops. The CMG control loops need to run at 5Hz and will use the SPHERES' PADS data. In order for the stable attitude control of the INSPECT system to be possible, the attitude controller must be able to accurately evaluate the spacecraft's orientation and rotation state at each cycle of the guest scientist program. To do so, the controller will pull the SPHERES current state from the internal IMU. With these rotation parameters and the target parameters set by the test case, the CMG attitude controller will be able to provide a desired torque to be sent to the CMG mixer. In addition, for the CMG mixer to be able to produce an appropriate gimbal rate for the desired torque, the SPHERES CPU will need to pull the current state of each CMG to the guest scientist program. This will include values for gimbal position (in radians), gimbal rate (in radians per second), and flywheel rate (in RPM). Each of these values will be used to calculate the angular momentum vector created by each CMG in the SPHERES coordinate system. The sum of the four angular momentum vectors is what is used to determine the rotation of the spacecraft.

4.2.5 INSPECT Data Flow (GP, BC, HS)

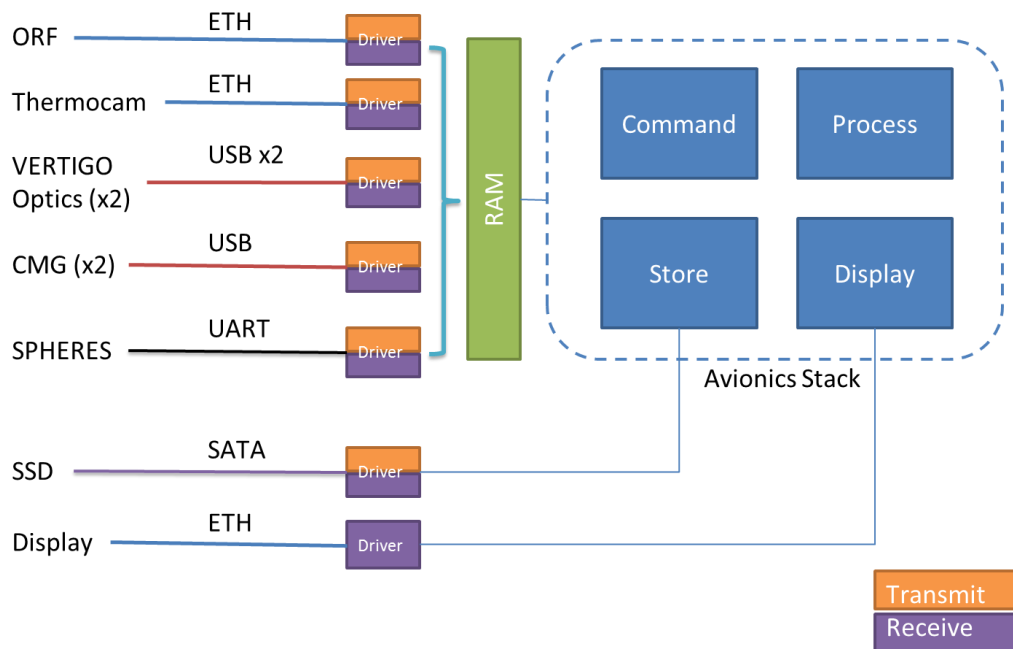


Figure 74: INSPECT Data Processing Flow (HS)

4.2.5.1 Overview and Desired Functionality (GP, HS)

In order to fulfill the goals of Navigation and Inspection, INSPECT should provide a platform for software and algorithm augmentations to SPHERES. The goal is to augment the current capabilities of SHPERES to incorporate the new sensor information available from additional hardware. INSPECT will be able to obtain sensor information from the new hardware and store it in the VERTIGO Avionics Stack's hard drive.

4.2.5.2 Timing Analysis (HS)

A worst-case timing analysis was performed to ensure that the INSPECT system is capable of handling the data provided by its sensors. For this analysis, the typical 1Hz localization/thrusting cycle for SPHERES was adopted as the time limit that the sensors had to meet. In order to meet the minimum operational requirements, each imaging sensor had to expose its CCDs, read off their values, download them internally, and then transfer them over to the VERTIGO Avionics Stack. Since the Avionics Stack handles these operations independently of SPHERES, the thrusting and CMG control portion was excluded from the analysis. The exclusion is further justified by the fact that the information required for position and attitude determination and control is negligible compared to (though higher priority than) the information being transferred for the imaging sensors.

This analysis revealed that in the 1Hz case, if each sensor were to return a single image per cycle, the total amount of time required would fit well within the cycle period, even if all operations were blocking (which they do not have to be) and the Avionics Stack had to wait on each sensor every time.

Table 34 Worst-case timing analysis.

Component	Operation	Time Needed (ms)
-----------	-----------	------------------

SPHERES		
	PADS/Thrusters*	400
	CMGs	10
ORF		
	Expose CCD	20
	Read/Download CCD**	50
	Transfer data	43
ThermoCam		
	Expose CCD	12
	Read/Download CCD**	50
	Transfer data	0.72
VERTIGO Goggles		
	Expose CCD	20
	Read/Download CCD**	50
	Transfer data	150
Total Time		255.72

* PADS/Thrusters time is for SPHERES only, and is excluded from Avionics Stack timing

** Time required to read and download CCD values is unknown (unclear from documentation whether the values given for operation time include this period), so a 50 ms value was included for each one, assuming that hardware performance was proportional to the amount of data to be read off

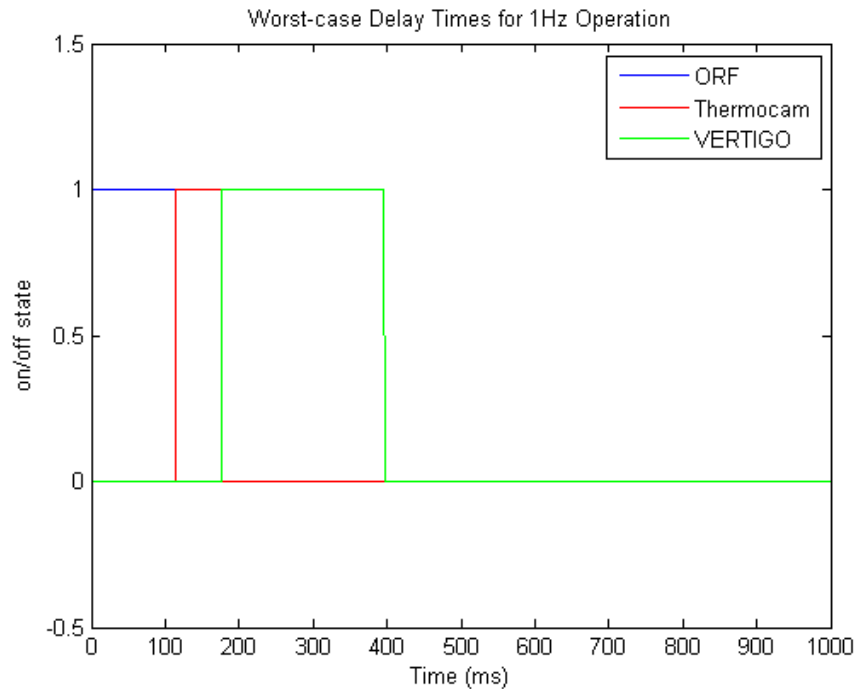


Figure 75 Worst-case delay analysis, presented as a timing diagram as part of a 1 Hz operation cycle for all sensors.

4.2.5.3 On-board Processing using the VERTIGO Avionics Stack (HL)

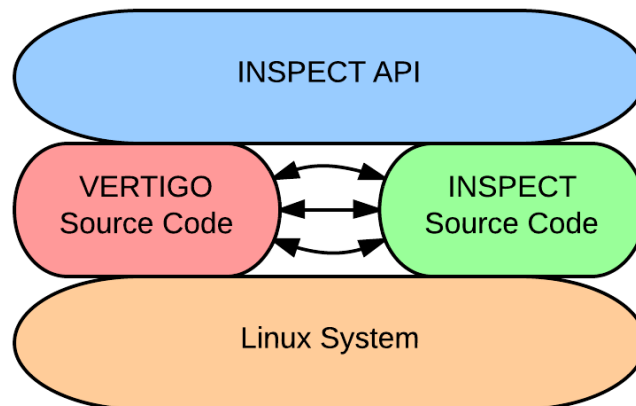


Figure 76. Software Design for INSPECT operations using the VERTIGO Avionics Stack (BC, GP)

The VERTIGO Goggles program is mainly composed of two high-level sets of programs, Goggles Daemon and Goggles Program Files (GPF). The Goggle Daemon runs on the background and supports GPF. The main functionalities of Goggles Daemon include running the Linux Daemon, communication, hardware monitoring, GSP support, debug service, and error reporting and fail-safes. GPF provides workspace for various Goggles Linux Software executable files and parameters files that can be readily implemented and compiled.

The ThermoCam and the ORF APIs can be installed under GPF. This allows simultaneous thread actions of each subsystem. The VERTIGO Optics Mount takes four different values per pixel, $[x, y, D, G]$, where D and G refer to the depth and the gray scale, respectively. The ThermoCam captures $[x, y, T]$, where T refers to the temperature. The ORF takes $[x, y, D, G]$, where the purpose is mainly focused on grabbing the depth values. These gathered data are then processed and transferred to GSP for future software developments and implementations.

4.2.5.4 Off-board Processing (HS)

Off-board processing is not an INSPECT requirement. However, as INSPECT is a risk-reduction project for future endeavors, consideration has been given to how off-board processing might be beneficial to the platform and how it might be done.

Off-board processing may be conducted in two ways pending additional development after 16.83x. One way is to do the processing on the data after the SPHERES has finished a set of maneuvers, and the inspection data has been passed off to another- likely more powerful- computer after an experiment run. The other way to do it would be to stream the data over a live connection as the SPHERES is running, which would allow much more immediate data processing that could even be sent back to SPHERES to close a control loop.

One possible platform on which this could be done is the Robot Operating System (ROS). Using this system would allow connections to be programmed in that link an active SPHERES to an off-board computer, and leave only “nodes” of code that are required to run the SPHERES itself on the VERTIGO Avionics Stack. Under this method, all processing of information would be passed off to nodes that exist on another computer, granting the capability to use a more powerful computer for operations than the Avionics Stack without having to upgrade the SPHERES hardware itself. This modification presupposes hardware that would allow a wireless link between

SPHERES and an external computer, and modification on the software to modularize it enough to run ROS.

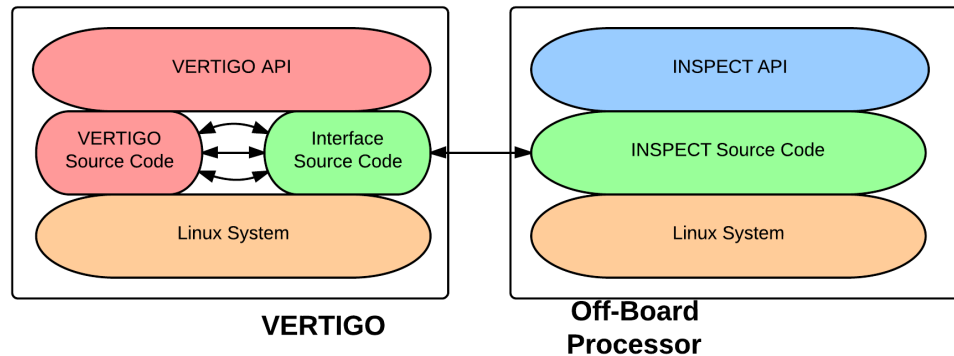


Figure 77: Software architecture for processing off-board the VERTIGO Avionics Stack (BC,GP)

4.3 Structures

4.3.1 Halo Interfaces (JB,NC)

The Halo system has six Halo ports for electrical, data, and mechanical interface. The Halo Port footprint diagram, found in Figure 31, outlines the mechanical interface. It comprises two similar squares of screws, with the inner square consisting of screw holes for outboard-to-inboard screw insertion. A second outer square consists of screw holes for inboard-to-outboard screw insertion into additional threaded female screw holes on the peripheral subsystem being connected. The Halo system includes four captive screws on each port face that join the peripheral system being attached and the Halo via the outer screw holes. These screws are equipped with washers to ensure that they do not penetrate too deeply into the peripheral system which could potentially damage the systems (NC).

A 50-pin ERF8-025-01-S-D-RA-TR female Samtec connector is also present and facilitates both data and power flow both to and from the sensors via a PCB.

Each Halo port sits at a 45-degree angle to its neighbor(s). Three are oriented facing the positive X direction and three in the negative X direction, although four (two on each side) are angled in the positive or negative Z direction by 45 degrees. See Figure 30 for visual representation.

4.4 Thermal Considerations (HM, MK, NC)

4.4.1 Overview (MK, HM)

The thermal analysis below was conducted to validate the health and safety of INSPECT subsystems over the length of mission operations. The primary concern was overheating of components, primarily the Optical Rangefinder (ORF) and Thermographic Camera (ThermoCam), above maximum operational temperatures prior to meeting the required 30 minutes of operation time.

The maximum operating temperatures for the components of interest are detailed in Table 35. Note that the upper and lower operating temperature bounds are similar for all systems, with greater variation in survival bounds.

Table 35: Thermal Ranges

Component	Min Operating Temp [K]	Max Operating Temp [K]	Min Survival Temp [K]	Max Survival Temp [K]
MESA SR4000 (ORF)	283	323	263	343
FLIR A5 (ThermoCam)	288	323	133	343
HoneyBee CMG	288	323	253	358
VERTIGO Electronics	288	333	263	343

4.4.2 Assumptions (HM, updated by MK)

In order to perform the thermal analysis of INSPECT, the following assumptions were made about the thermal characteristics of system:

- 100% of power drawn by each system is converted to heat
- Systems generate heat as uniform solids
- In worst case scenarios, systems draw their maximum power continuously until failure
- The distance between Halo ports is sufficient to prevent individual subsystems from thermally affecting neighboring ones

4.4.3 Method of Thermal Analysis (NC, MK)

To model the flow of heat through the components, SolidWorks' thermal simulation tools were utilized. The simulation was performed using an ambient temperature of 295 K as this is the temperature in the ISS, and using an assumption of non-negligible convection, as this is the environment during flat-floor testing. Although natural convection does not occur on the ISS, forced convection via air currents would result in nearly the same heat loss.(NC)

Based on the power draw data in Table 36, the Optical Rangefinder (ORF) was the component of greatest concern. The ORF and the Thermographic Camera (ThermoCam) use the same aluminum mounting structure (detailed in Sections 4.1.3.3 and 4.1.4.3) which also serves as a heat sink. The ORF specifications indicated an average power draw of 12W, which is the power draw used in the analysis to follow. It should also be noted that the average power draw measured after component delivery was found to be significantly lower at 4.64W, so the thermal analysis conducted represents a worst-case scenario. Since the ThermoCam only draws an average 3W of power using the same mount, a separate ThermoCam analysis from the ORF was not necessary, as verification of ORF thermal requirements would also verify ThermoCam thermal requirements. (NC) As a mature system already on the ISS, the VERTIGO Avionics Stack and Optics Mount have already passed thermal testing; as such, further analysis was not deemed necessary. To prevent overheating, the VERTIGO electronics system has a forced convection system in the control box in addition to safety kill switch triggered at 60° C that cuts power to VERTIGO.

Table 36: Power Draw by Subsystem

Component	Average Power Draw [W]	Maximum Power Draw (Spec) [W]
Mesa SR4000 (ORF)	4.64 (measured)	14.40 (spec)
FLIR A5 (ThermoCam)	3 (measured)	6 (spec)
HoneyBee CMG	7	11
VERTIGO Optics Mount	1.45	10.8 (allocated)

4.4.4 Thermal Analysis (NC, HM)

Using the Solidworks simulation on the Optical Rangefinder (ORF) in its mount, it was found that, given a total power draw of 12W, the sensor reached equilibrium at approximately 305 K, well below the maximum operating temperature of 323 K. This simulation suggests that the ORF sensor will never overheat given adequate ventilation. Furthermore, all of the electrical components and the interface with Halo remained much cooler at around 297 K. As such, the ORF and ThermoCam are expected to operate without approaching maximum operating temperatures for our required mission length. (NC)

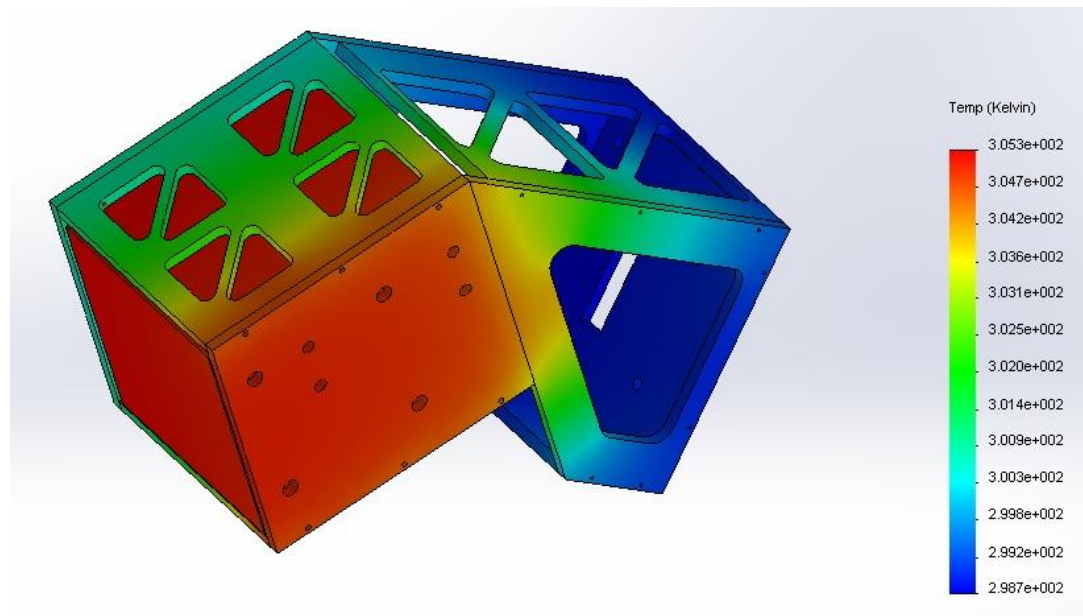


Figure 78: Thermal Analysis on ORF Mount (NC)

5 Risks and Mitigations

Expected risks for each subsystem as well as the fully integrated system are outlined in this section, along with mitigations taken to minimize the likelihood and/or impact of these risks.

5.1 VERTIGO Goggles (HL)

Table 37: VERTIGO Goggles Risks and Mitigations

	Description	Mitigation
A	VERTIGO Avionics Stack boot and storage drives are not properly installed.	Failed boot and storage drives can be always reinstalled.
B	VERTIGO system crashes during software development	Most of system crashes occur as a software crash. The operating system can be reinstalled and thus reducing the impact. However, there are possibilities of loss of software programs.
C	Data rate is too much to handle both eyes operating on VERTIGO Goggles	VERTIGO Optics Mount takes the frame rate from the parameter file. Users can lower down the FPS.
D	We cannot properly integrate and align data from peripherals into a 5D voxel	For 16.83x INSPECT requirement is not to integrate and align data, but to output gathered sensor data.

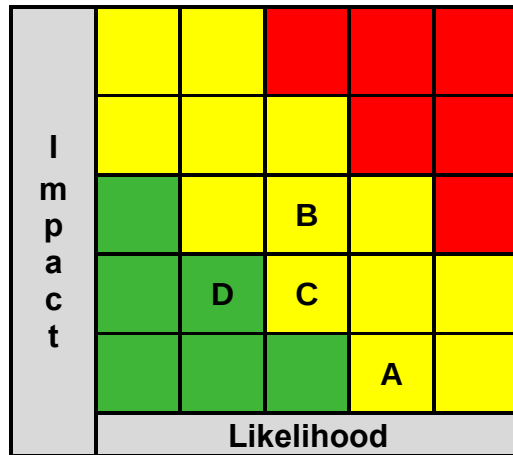


Figure 79: VERTIGO Goggles Risk Fever Chart

5.2 Optical Rangefinder (ORF) (MV)

Table 38: Optical Rangefinder: Risks and Mitigations

	Description	Mitigation
A	ORF interferes with US/IR Metrology	Testing shows that operating the ORF at 1 image per second increases the error in the metrology system to less than 150% of its original value.
B	Varying Halo battery voltage damages ORF	A voltage regulator on the MIC PCB protects the ORF from changes in the battery voltage.
C	The ORF mount structure does not provide sufficient heat dissipation	Thermal analysis of heat dissipation in microgravity. Experimental measurement of heat dissipation in 1G.*

*Convection currents about the warm device chassis are driven by gravity acting on a density gradient within the air. In microgravity, there will be substantially less convection, and the thermal resistance of the boundary between the air and the chassis will be higher. This will increase the device's steady-state temperature at a given power level.

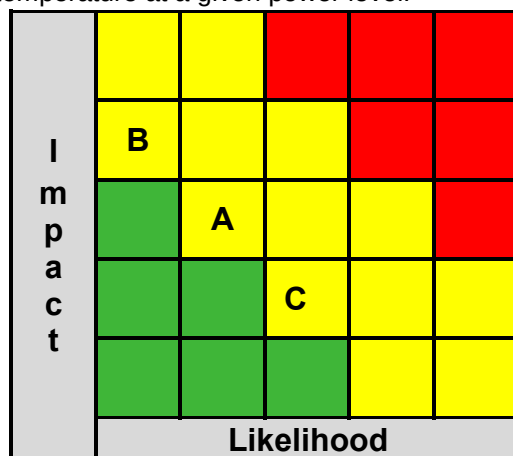


Figure 80: Optical Rangefinder Risk Fever Chart

5.3 Thermographic Camera (ThermoCam) (KAF)

Table 39: Thermographic Camera Risks and Mitigations

	Description	Mitigation
A	Data capture immediately after powering ThermoCam causes inaccurate temperature readings	Wait 10 minutes after powering on ThermoCam for calibration before taking data
B	Necessary calibration time drains battery life, not allowing for full 30 minute operation length	Analyze percentage of battery drainage and how it affects the operation length possible
C	The ThermoCam mount structure might not provide sufficient heat dissipation and affect data accuracy	Thermal analysis of aluminum mount structure carried out by structures team and ThermoCam data analyzed for accuracy. Modification of the mount structure design if accuracy is significantly affected.

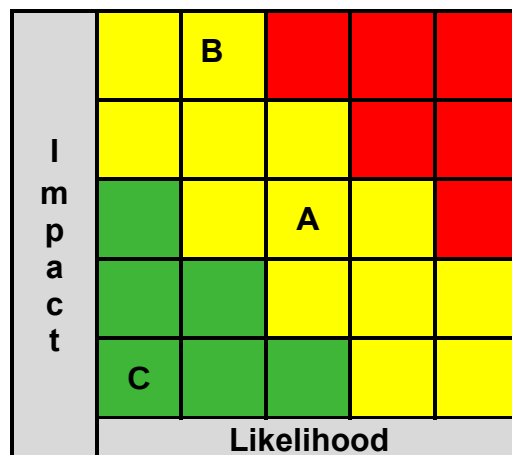
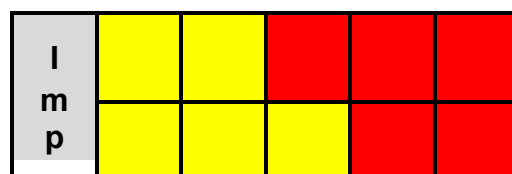


Figure 81: Thermographic Camera Risk Fever Chart

5.4 CMGs (JK)

Table 40: CMGs Risks and Mitigations

	Description	Mitigation
A	CMG control box is not compatible with Halo physically or electrically	Correct interfaces can be procured or machined
B	Power draw from CMGs is too great to sustain battery power for 30 minutes	Analyze potential power-saving setups
C	Honeybee Code is not compatible with VERTIGO software environment	Develop INSPECT ACDS software from scratch



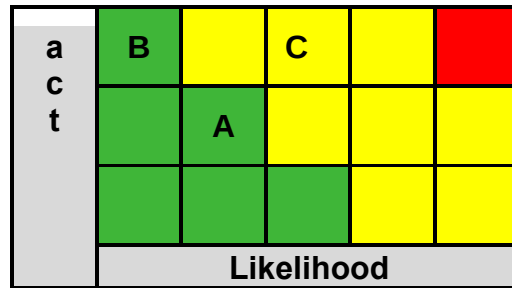


Figure 82: CMGs Risk Fever Chart

5.5 System-Level Risks (MK)

The following risks have the potential to impact the ability of INSPECT to meet systems-level requirements and/or significantly delay further development of the INSPECT system. The status of each of the risks below should be tracked throughout the course of the project to assess when and which mitigation plans should be employed.

Table 41: System Technical Risks and Mitigations

	Description	Mitigations
A	Peripherals interfere with SPHERES ability to communicate with beacons	Future flat floor testing should place beacons at varying levels to increase chance of signal reaching SPHERES. Wiring on INSPECT should be reduced when data lines are functional on Halo ports, which will reduce signal blockage.
B	ORF interferes with SPHERES IR metrology during future testing with multiple SPHERES	Verified ability of ORF to turn off LED and conducted preliminary research to synchronize ORF with SPHERES, but needs further exploration for future multi-SPHERES configs
C	System or testing hardware are structurally/electrically damaged during testing	Testing subsystem components on VERTIGO emulator and VERTIGO Avionics Stack prior to integration, adherence to pre-determined test plans and purchase of multiple MICPCBs and board components in case of damage
D	Delays in reaching full Halo functionality impact INSPECT schedule	Open communication with Halo team, use of Ethernet switch and Optics Mount Ethernet port to provide data transfer while Halo data lines are not functional. Construction of testing structures with Halo mechanical interface footprint to mount peripherals to conduct simulations using external power supplies.
E	CMG controller board repair (for current anomaly in CMG port 2) delays further integration	Open communication with Honeybee and Draper Labs, use of controller board as is when connected to external power supply
F	CMG-VERTIGO software integration impacts INSPECT schedule	Open communication with Honeybee to facilitate understanding of CMG software, ensure CMG software team is experienced with serial communications systems
G	Vibrations due to CMGs reduce image accuracy	Vibration dampeners have been incorporated into CMG mounting system, significantly reducing vibrational effect on other peripherals
H	MICPCB inability to monitor system health leads to damage to boards and/or peripherals	Another iteration of MICPCB design should be carried out to include an LED that reports the status of peripheral component

I	System mass imbalance affects actuation	Ensure wiring does not create irregularities in mass distribution that would impact navigational path
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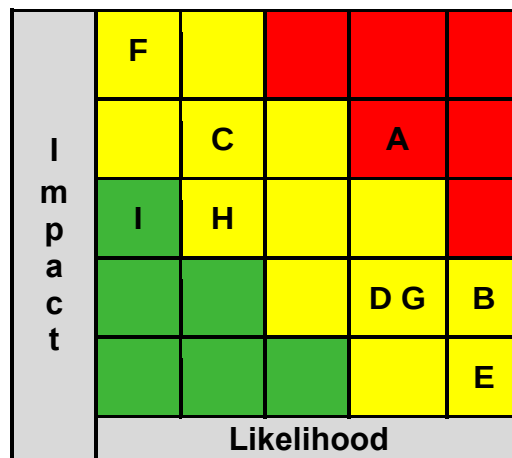


Figure 83: System Risk Fever Chart

6 Integration and Test

6.1 Assembly, Procurement and Integration Plan (GK)

Throughout February, the structures team worked to finalize design plans, including integration of the system mechanically and electronically to an air carriage, while subsystems acquired all necessary hardware and began their first round of preliminary testing. The ORF and ThermoCam were tested against vender specs and sensor requirements, including field of view measurements. Once these tests were accomplished and the VERTIGO team was familiarized with their system and its role in INSPECT, the subsystems moved on to stack testing with the SPHERES and VERTIGO Avionics Stack to evaluate software and data transmission. At the same time, the systems integration team completed the preliminary system test to evaluate the maximum testing time on the flat floor based on calculations for the weight of the system and its ability to translate using SPHERES thrusters. Upon completion of stack testing, the subsystems were attached to the Halo structure in single component testing to test functionality and electrical and mechanical mounting prior to a full system acceptance test. The final test completed was the full integrated system test, in which all components were integrated into the INSPECT system and the Concept of Operations maneuvers were completed on the flat floor. At that time, all sensor and system-level requirements were evaluated for full integration and functionality.

6.2 Testing Plan (JW)

The goal of the testing procedures is to verify all testable requirements, ensure subsystem integration, and reduce risk to the mission, operators, facilities, and system components.

6.2.1 MICPCB Testing (CL, CK)

The purpose of initially testing the MICPCBs separately from ORF and ThermoCam is to ensure that power and data can be successfully received and transmitted through the board before connecting it to the relevant sensors. The following procedure must be done for each populated MICPCB. Note that these are the testing procedures for the MICPCB without the health monitoring system.

6.2.1.1 Equipment Materials (CL, CK)

The equipment necessary for the initial MICPCB testing is as follows:

- Fully populated MICPCB
- DC power supply
- Alligator clips (2)
- Stripped wires (2)
- Power Resistors of varying resistance; 10, 11, 15, 20, 25Ω were all used to test the MICPCB
- Multimeter with probes
- Breakout cable with female Samtec 50-pin connector on one end (recommended but not necessary, more stripped wires could be used to probe the male Samtec 50-pin connector on the board to check for shorts, and other places on the board can be connected to power for the component tests)

6.2.1.2 MICPCB Inspection (CL, CK)

After the population of a MICPCB, visual inspection must be carried out by someone who was not involved in the soldering and population of that board prior to any testing. This intermediate step will catch a MICPCB with shorted out elements in the circuit or non-ideal soldering and will prevent it from being destroyed during actual testing. Multiple rounds of this intermediate testing could be used if the soldering was corrected. Inspection was carried out in the following steps:

1. Carry out a visual inspection of the board by someone who did not populate the MICPCB, under the microscope if necessary.
 - a. Check for visible shorts in the circuit.
 - b. Check for cold solder joints and other soldering problems. Re-solder if necessary, and then repeat the visual inspection steps.
2. Set the multimeter to beep mode, and use the multimeter to check for shorts in the circuit.
 - a. Ensure each pin on the 50 pin connector is not shorted to any other pin.
 - b. Ensure the 8 Ethernet pins are not shorted to any other Ethernet pin.
 - c. Ensure Vin- and Vin+ pins of the voltage regulator are not shorted together. Similarly, ensure Vout- and Vout+ pins are not shorted.
 - d. Ensure that power and ground pins of the screw terminal are not shorted.
 - e. Determine the ON/OFF position of the switch
 - i. For OFF position, check pins 1 & 2 are shorted together and are connected to ground. For the MICPCBs, the OFF position matches the position of the switch in the CAD outline printed on the surface of the board.
 - ii. For ON position: check pins 2 & 3 are shorted together. ON is opposite of the CAD outline of the switch printed on the surface of the board.

6.2.1.3 Single Component MICPCB Power Test Without Load (CL, CK)

After confirming that the MICPCBs are manufactured correctly and that all electrical connections are accurate, a power test (without a load in the circuit) will be conducted to verify that the MIC PCB is capable of receiving an unregulated voltage of 11.1V and output a regulated 12V. This test will be carried out in the following steps:

1. Ensure MICPCB switch is turned off.
2. Attach one stripped wire into the power terminal of the screw terminal and one into the ground terminal.
3. If a break-out cable with a female 50-pin connector is available, use that to connect to the male 50-pin connector. Otherwise, find pins/surfaces on the MICPCB that connect to power (Batt+) and ground (Batt-). Batt+ was connected to pin 2 on the switch and Batt- was connected to the Vin- pin on the voltage regulator during testing.

4. Set power supply to 11.1V and then turn the power supply off.
5. Connect power supply to Batt+ pins (7, 9, 11) and Batt- pins (1, 3, 5) on the female 50-pin connector break-out cable, if used. Otherwise, connect the power supply to the same connections or pins that were probed in step 3 for power and ground (pin 2 on the switch and the Vin- pin on the voltage regulator, respectively). During testing, the ground probe on the multimeter was connected to power supply's ground for ease of probing.
6. Turn on the power supply. Ensure that the power supply reads: Current = 0A, Voltage = 11.1V.
7. Turn on MICPCB.
8. Use the multimeter to check the following quantities:
 - a. Voltage across the two wires of the screw terminal (the output voltage) = 12V.
 - b. Input voltage remains 11.1V.
 - c. Current reading on the power supply < 0.05A.
9. Turn off MICPCB.
10. Turn off power supply.

6.2.1.4 Single Component MICPCB Power Test With Load (CL, CK)

After verifying that the MICPCB outputs 12V from an input of 11.1V, a power resistor load will be connected to the MICPCB to simulate the ORF or ThermoCam before actually connecting the sensors to the board. This test will be carried out in the following steps:

1. Connect a 15 Ω , 50W power resistor to the power and ground wires of the screw terminal. During testing, 11, 10, 15, 20, and 25 Ω resistors were used, iterating through these next steps for each resistor. If resistors with a resistance other than 15 Ω are used, the current draw expected on the power supply should be calculated accordingly.
2. Turn on the power supply. Ensure that the power supply reads: Current = 0A, Voltage = 11.1V.
3. Turn on MICPCB.
4. Use the multimeter to check the following quantities:
 - a. Voltage across the two ends of the resistor (output voltage) = 12V.
 - b. Input voltage remains 11.1V.
 - c. Assuming the voltage regulator is 75-90% efficient (as given in the data sheet for voltage regulator Delta S24SE12002PDF A DC-DC), input current (as read from the power supply) is 0.8-1.0A. Output current (current through the resistor) is approximately 0.74A. These current values depend on using a 15 Ω resistor load – if other resistors with differing resistances are used, expected current input and outputs should be calculated.

Once these steps have been completed, and the MICPCB has been verified to work as expected, the legs of the voltage regulator and Ethernet port need to be trimmed with wire cutters and filed down for the MICPCB to fit inside the mount structures. In addition, either the 50-pin connector side of the board or the adjacent side of the mount structure back plate needs to be covered with protective kapton tape to ensure that the MICPCB does not short against the aluminum plate.

(CL)

6.2.2 Imaging Sensor Software Integration and Testing (HS)

For all three imaging sensors (ORF, VERTIGO, and ThermoCam), software development and implementation is required to ensure proper communication with the VERTIGO Avionics Stack. The objective is to obtain images from all these sensors, and store them in a format accessible by OpenCV, which is the current image processing package being used on VERTIGO. Such a result

would allow current and future OpenCV processing to be done on all the sensor data at once, and build on an existing platform that has already been proven to work with VERTIGO.

To this end, certain software development and implantation steps were taken by all sensor teams. The ORF, VERTIGO, and ThermoCam teams were able to successfully implement their software simultaneously on the VERTIGO Avionics stack in individual terminal windows. (AW)

6.2.2.1 Integration and Testing Milestones

1. Install sensor driver on VERTIGO emulation
2. Verify sensor communication with VERTIGO emulation
3. VERTIGO emulation commands sensor to take an image with GUI
4. VERTIGO emulation commands sensor to take an image with API
5. Pass data from sensor to VERTIGO emulation in OpenCV-accessible format
6. Store data from sensor on VERTIGO emulation computer's hard disk
7. All steps repeated on VERTIGO Avionics Stack

6.2.3 VERTIGO Stack Testing (AL, HL)

6.2.3.1 Objective

The purpose of VERTIGO Stack Testing is to demonstrate the functionality of the peripheral systems when connected directly to the VERTIGO Avionics Stack. Each subsystem must demonstrate its ability to individually send and receive data to and from the Avionics Stack. The Avionics Stack must not only be capable of commanding each peripheral system to perform its tasks, but must also be able to process received data and still maintain control authority over SPHERES. Stack Testing serves to simulate full INSPECT functionality on a preliminary level. Systems will still communicate through the Samtec 50 pin connector on the Avionics Stack that they will interface with when connected to Halo. After sensors have been individually verified with VERTIGO, the MICPCBs will be tested and used as the interface between Halo and the sensors.

6.2.3.2 Personnel

During Stack Testing, members of the VERTIGO Subsystem Team, as well as members of the tested peripheral subsystem and members of the Avionics subsystem must be present. Systems Integration and Systems Lead team members of the INSPECT team shall also be present.

6.2.3.2.1 Core Personnel (present during all subsystem stack testing)

VERTIGO Team

- Alessandro Lira
- Hang Woon Lee

Avionics Team

- Candice Kaplan
- Connie Liu

Systems Integration

- Grace Krusell
- John Wenzel

Systems Leads

- James Byrne
- Melissa Kornspan

6.2.3.2.2 Peripheral Systems Personnel (present during relevant subsystem stack testing)

ORF Team

- Matthew Vernacchia
- Katherine Hobbs

ThermoCam

- Krystal Arroyo-Flores
- Alex Wassenberg

CMGs

- James Krasner
- Matthew Abel

6.2.3.3 Location

Individual Stack Testing will take place in the MIT Space Systems Laboratory in room 37-372 on the SSL Glass Table.

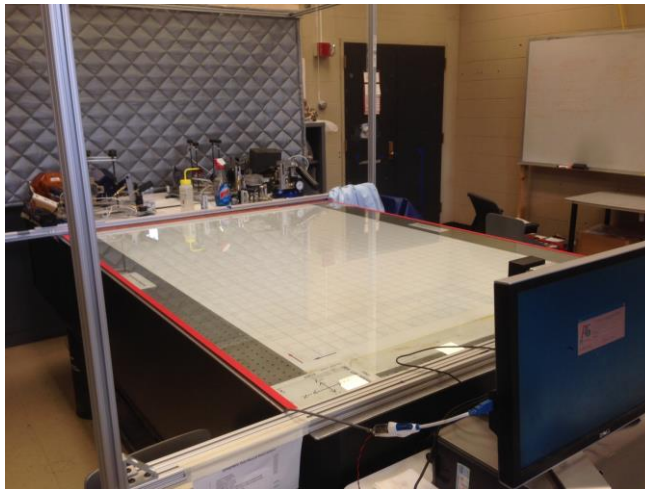


Figure 84: SSL Glass Table

6.2.3.4 Equipment Materials

The Equipment necessary for VERTIGO Stack Testing is as follows:

- Laptop with SPHERES/Halo GUI installed
- Ethernet cable
- SPHERES
- INSPECT-grade air carriage
- Halo structure
- VERTIGO Optics Mount (for VERTIGO team single component stack testing only)
- VERTIGO Avionics Stack
- USB Flash Drive
- Charged Nikon rechargeable battery pack (at least 10 batteries)
- SPHERES battery shells; sufficient rechargeable AA batteries
- DC Power Source

In addition to the equipment and materials listed above, each subsystem will need equipment specific to its needs.

ORF Team

- MESA SR4000 (ORF)
- Power and data interface board (MIPCB) to connect the ORF to the Halo port
- Wiring to connect the ORF to the MIPCB and to the central Ethernet switch
- ORF mount structure

ThermoCam Team

- FLIR A5 Thermographic Camera (ThermoCam)
- Power and data interface board (MIPCB) to connect the ThermoCam to the Halo port
- ThermoCam mount structure

CMG Team

- Four LEO-H120-T50 Control Moment Gyroscopes (CMGs)
- Structures CMG mounting plates
- Power and data interface board for CMG PCB

6.2.4 CMG Single Component Testing Structures

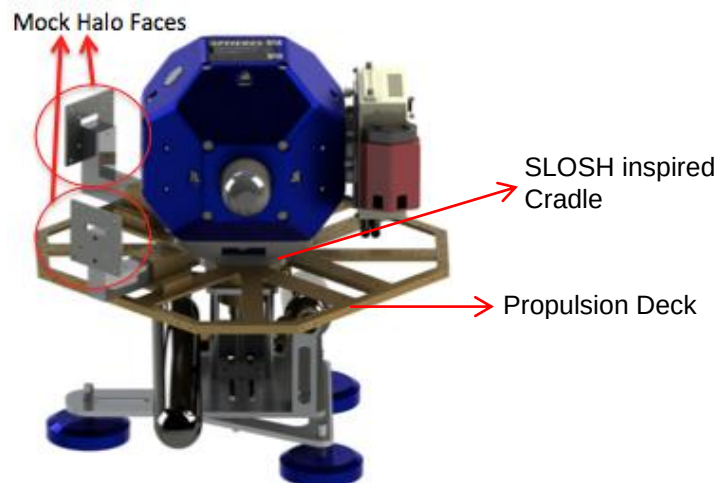


Figure 85: CMG Flat Floor Single Component Testing Structure

Figure 86: Bare CMG Flat Floor Testing Structure (Top) shows the 90 degree relationship between the mock Halo faces. Figure 87: CMG Flat Floor Testing Structure shows the single component system as a whole. Note: as the CMGs are our heaviest subsystem, counterweights will be required to even out the mass distribution. These counterweights (not shown in the figure) will be placed so as to resemble the full system center of mass in the z-x plane as well as the y axis moment of inertia. This will prove to be useful for our CMG control software.

In order to provide the ability to test in the SSL, the structures team developed a lazy susan setup. Utilizing this setup, future CMG teams can test certain rotational maneuvers at the convenience of the SSL bench.

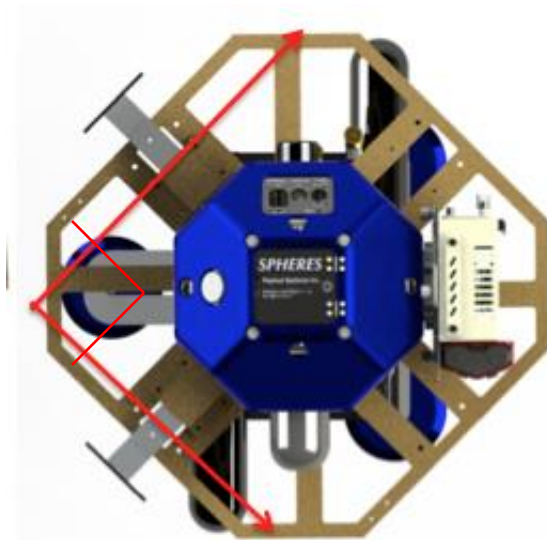


Figure 86: Bare CMG Flat Floor Testing Structure (Top)

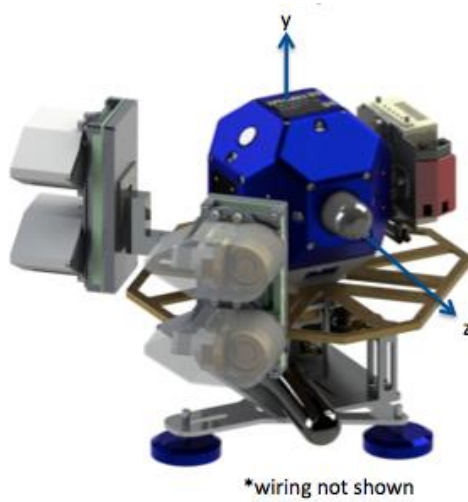


Figure 87: CMG Flat Floor Testing Structure

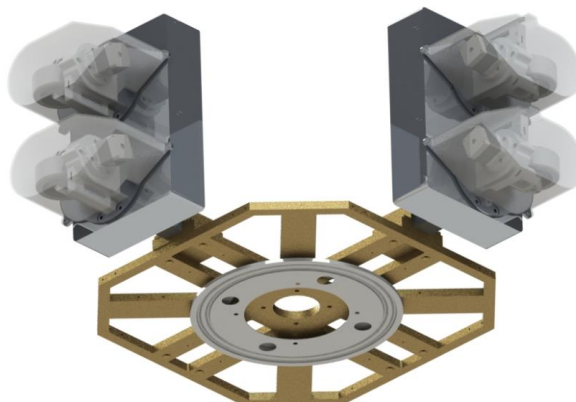


Figure 88: Alternative Bench Setup Utilizing Lazy Susan

6.2.4.1 Requirement Verification

Table 42: Stack Testing System Requirements

System Requirements					
S-3	Power Limit	The system shall not exceed a peak power draw of 16.65 watts at each port. (11.1V and 1.5 amps)	M-1	Excessive power draw will present health risks to avionics, decreasing mission lifespan.	Testing
Verification		Verified – ORF requires greatest power draw of 13.36W			
Halo Requirements					
H-2	Data Connection	Each suite component shall be able to connect to the Halo via USB 2.0 or Ethernet	S-4	SPHERES will be utilized as the foundation for the sensor/actuator suite	Analysis & Testing
		Verified – All subsystems have been successfully connected to a computer using USB 2.0 or Ethernet			
Verification		Unverified – Halo Integration Testing scheduled for 18Apr – 25Apr			
INSPECT Suite Requirements					
I-1	ISS Operation Time	The system shall be capable of operating for no fewer than 30 minutes without refueling or recharging.	M-1	Needs to limit the amount of fuel and power used by INSPECT so that future EVA operations are a reasonable amount of time	Analysis
Verification		Unverified – Halo single component testing scheduled for 14Apr – 18Apr			
I-8	Sensor Placement	The sensors shall point in the same direction and be placed no more than 50cm apart.	SX-1, SX-2	Allows for combined field of view for sensors	Inspection
Verification		Verified: CAD models and machined mounts designed and inspected to confirm			

6.2.4.2 Success Criteria (AL, HL)

The success of this test will be measured by the VERTIGO Avionics Stack's ability to receive input from the Optics Mount, the ORF, the ThermoCam and the CMGs through Halo, make appropriate on-board calculations, and give resulting commands to the INSPECT system

- If the Avionics Stack is able to receive images from the the Optics Mount, the ORF, and the ThermoCam, then VERTIGO will meet criteria H-2
- The SPHERES operating with Halo and the Optics Mount attached must not exceed its allotted power budget when connected to a power source in order to meet criteria S-3
- If the system still has power after being disconnected from a DC power source for over 30 minutes while doing standard testing operations, then the system will meet criteria I-1
- If the VERTIGO Avionics Stack is able to process images from the Optics Mount, the ORF, and the ThermoCam during testing at least every 2 seconds, then criteria I-8 will be met
- If the VERTIGO Avionics Stack is not able to make the appropriate computations in a real time environment, the software being used to operate Halo and VERTIGO may need to be revised.
- If, after multiple revisions testing attempts, it is apparent that the VERTIGO hardware is not capable of commanding the INSPECT array with only one sensor attached (in the form of the

Optics Mount), then other options for the INSPECT on-board computer may need to be considered.

6.2.4.3 Tasks to be completed prior to testing (AL, HL)

6.2.4.3.1 Software (HL)

In order to proceed with VERTIGO Stack Testing, all peripheral sensors' compatibility and functionality must be verified during VERTIGO Emulation Testing. VERTIGO Emulation provides almost exact software environment setting to that of actual Avionics Stack, thus enabling each sensor to test without any risk of damaging actual Avionics Stack.

6.2.4.3.2 Test preparation

1. Charge at least 10 Nikon EN-EL4 batteries for Halo and the VERTIGO Avionics Stack
2. Download GPF (Goggles Program File) to VERTIGO Goggles
3. Calibrate VERTIGO cameras using "Camera Calibration"
4. Clear space in SSL bench area for testing

6.2.4.4 Setup

- Mount Halo to a SPHERES
 - **Using standard Halo procedure to be determined*
- Mount the VERTIGO Optics Mount to Halo
 - **Using standard Halo procedure to be determined*
- (Conditional) Start Halo/INSPECT software on a laptop
 - **Dependent on whether Halo will have a software interface for an external test computer*
- Prepare SPHERES battery packs with kapton tape
- Connect SPHERES to a DC Power Source

6.2.4.5 Procedure

**Note: The test procedure is intentionally inexplicit, as the exact software testing nature of Halo has not yet been determined. This test plan will be updated to comply with standard Halo/INSPECT procedure.*

1. Power on the INSPECT system
2. Establish communication between Halo and SPHERES with Halo/INSPECT GUI
 - a. GUI should display contact with the SPHERES, including its ID and communication method
3. Run BlobTrack test program using steps similar to preliminary testing
 - a. Change parameter file of BlobTrack to vary frequency of image capture

- b. Test BlobTrack program at frequency of 0.5 Hz, 1 Hz, and 2 Hz
4. Power INSPECT system off.
5. Replace SPHERES DC power source with battery packs
6. Replace Halo and VERTIGO battery packs with freshly charged packs
7. Power INSPECT system on
8. Establish communication between SPHERES, VERTIGO, and Halo systems
9. Run BlobTrack for at least 30 minutes at frequency of 0.5 Hz on solely battery power
 - a. Record elapsed time until low battery warning shows on VERTIGO Avionics Stack and/or on the SPHERES
10. Quit BlobTrack test program
11. Power INSPECT system off.
12. Power INSPECT on, retrieve battery and data-usage log files from VERTIGO, (using USB key if necessary), power off INSPECT
 - a. More detailed explanation of batter usage data retrieval in VERTIGO preliminary test plan document

6.2.4.6 Tasks to be completed prior to termination of testing

- SPHERES, Halo, and VERTIGO should be properly stored after use
- Batteries shall be removed and recharged for future testing
- Calculation of INSPECT power will be derived from the battery data from VERTIGO, or observed from the DC Power Source

6.2.4.7 Test Results

The results will be used to verify the various criteria from Section 3. The power draw requirements and usage S-3 and I-1 will be determined by examining the battery log files. The data, communication and processing criteria will also be evaluated in compliance with H-2, and I-8 respectively.

Testing Results Table

Criteria	Test	Result	Pass(Y/N)
S-3	Measure power draw from SPHERES using DC power source and power draw from VERTIGO using battery log files. The total power draw must		

	not exceed 55.5 watts		
H-2	Establish communication between the Optics Mount and Avionics Stack through Halo. The Avionics Stack must be able to recognize the Optics Mount and receive and send data.		
I-1	Record elapsed running time of test on solely battery power while running low frequency BlobTrack test program. The system must be able to run the program for at least 30 minutes		
I-8	Processing of images files from Optics Mount into useful BlobTrack data at a frequency of at least 0.5 Hz constitutes calculations on the order of 0.3 GFLOPs. The test program must be able to run at 0.5 Hz		

6.2.4.8 Future Testing (AL, HL)

Future testing must involve running a similar test procedure while the INSPECT system is mounted on an air carriage. If the system is capable of running on an air carriage, the testing will proceed to final integration testing of INSPECT with all sensors and the CMG units present connected to the VERTIGO Avionics Stack.

6.2.5 MICPCB Integration Tests (CL, CK, KAF)

The integration of the MICPCBs occurs after the successful integration of ORF and ThermoCam with the VERTIGO Avionics Stack and Halo. This series of tests is to check the ability of the MICPCB to successfully integrate with Halo and to provide the correct power to the ORF and ThermoCam such that all sensors are powered and able to take data. After testing the board as outlined in previous sections to ensure that it was working as intended, the board was attached to Halo via the 50-pin connector and attached to the ORF or ThermoCam using their respective

connectors. Because Halo did not route data on either the ORF or ThermoCam ports, the sensors did not plug into the Ethernet connector on the MICPCBs, instead routing data through an Ethernet switch and then to the VERTIGO Avionics Stack. The MICPCB was tested to deliver power to the sensors and was found that it powered up both sensors and that they could transfer data through the Ethernet switch while routing power through the MICPCBs.

6.2.5.1 MICPCB and Halo (CL, KAF)

The first step of integration is to connect the MICPCB to Halo without any other sensors or equipment and power Halo on to power the MICPCB. This test will be conducted only after the MICPCB has passed the previous inspection and single-component power tests. This test will be carried out in the following steps and repeated twice (once for the ORF PCB connected to the Halo Port #1, and once for the ThermoCam PCB connected to the Halo Port #5):

1. Turn Halo off. Connect the MICPCB to the Halo port, as shown in Figure 89.
2. Check for electrical shorts between ground and Batt+ and ground and Vout+ on the MICPCB.
3. Turn Halo on. As of May 2014, Halo ports do not have individual power switches, so turning on Halo will provide power to all Halo ports.
4. Measure input and output voltages on MICPCB (0 V for both measurements).
5. Switch on MICPCB.
6. Measure input and output voltage on MICPCB (approximately 11.1 V and 12 V respectively), as shown in Figure 90.
7. Switch off MICPCB.
8. Turn Halo off.

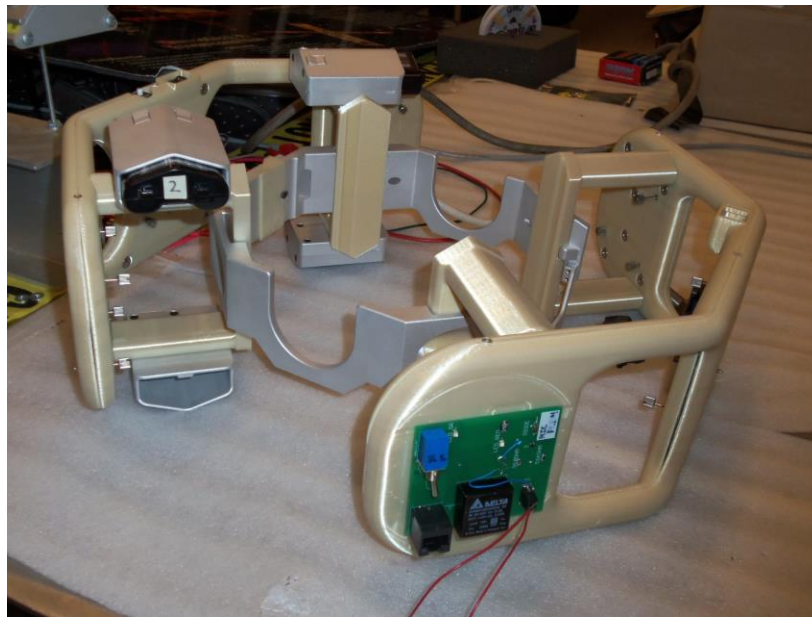


Figure 89: MICPCB and Halo setup (CL)



Figure 90: MIC PCB connected to Halo; verifying 12 V output from PCB (CL)

6.2.5.2 MICPCB, Halo, and a Single Sensor (CL, KAF)

After verifying the appropriate voltage input to and output from the MICPCB via Halo, a single sensor (either the ORF or the ThermoCam) is connected to its respective MICPCB and corresponding Halo port to test if the board is able to power the sensor using Halo power.

1. Connect the sensor to the MICPCB via the screw terminal.
 - a. For the ThermoCam: Connect the M12 end connector to the ThermoCam and connect the power and ground wires to the appropriate terminals on the screw terminal.
 - b. For the ORF: Connect the M3 connector to the ORF and connect the power and ground wires to the appropriate terminals on the screw terminal.
2. Turn Halo on.
3. Switch on MICPCB.
4. Check that the sensor has been powered on.
 - a. For the ThermoCam: It will click twice for its initial calibration and the blue indicator light on its rear face will be on, as shown in Figure 91.
 - b. For the ORF: The ring of red LEDs on its front face will be on, and the green indicator light on its rear face will be on.
5. Switch off PCB.
6. Turn Halo off.

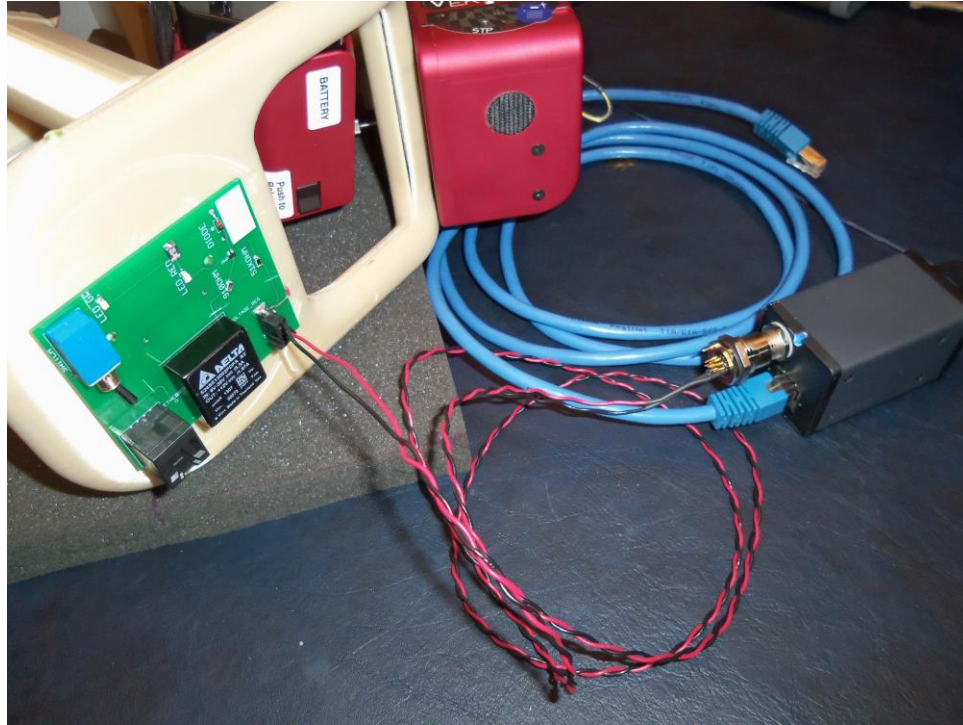


Figure 91: ThermoCam being powered by MIC PCB and Halo (blue indicator LED is on) (CL)

6.2.5.3 MICPCB, Halo, a Single Sensor, and Ethernet Switch (CL, KAF)

Because there is currently no data connection on the Halo ports to which the ThermoCam and ORF will be connected, it is not possible to test data on the MICPCB, including data pins on the male 50-pin connector, RJ45 Ethernet port, and the differential pair traces. Instead, an Ethernet switch is used as a replacement (see Figure 92 and Figure 93). The Ethernet cables coming from the sensors will be connected to two ports in the switch, and a third Ethernet cable will connect the switch to an Ethernet port on the VERTIGO Avionics Stack. The data and images being transmitted from the ThermoCam, ORF, and VERTIGO Optics Mount via Ethernet can be viewed on a computer by connecting the VERTIGO dongle from the Avionics Stack to the computer.

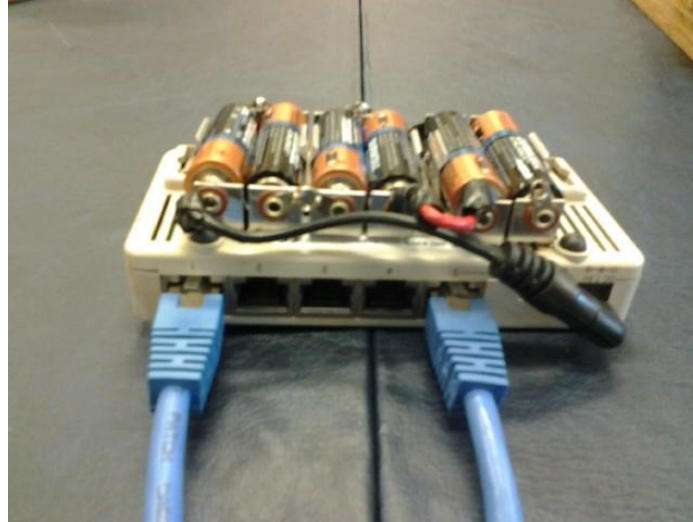


Figure 92: 10-100 Ethernet switch used for data transfer during MICPCB, Halo, sensor interface testing; ThermoCam and VERTIGO Avionics Stack connected (ports #1 and #5 respectively) (KAF, CL)



Figure 93: Gigabit Ethernet switch to be used during flat floor testing (CL)

Initially, the Ethernet switch will not be connected to the Avionics Stack but will instead be directly connected to a computer:

1. Connect one end of Ethernet cable to ORF or ThermoCam and the other end to the Ethernet switch (port #1 if ThermoCam, port #2 if ORF). Connect one end of another Ethernet cable to port #5 and the other end to a computer.
2. Turn on the Ethernet switch. An LED indicator light should turn on.
3. Turn Halo on.
4. Switch on MICPCB.
5. Verify successful data streaming:
 - a. For the ThermoCam: The ThermoCam GUI on the computer is receiving images sent by the ThermoCam.
 - b. For the ORF: The ORF is sending images and those images can be displayed on the computer.
6. Terminate data streaming from the sensor using the laptop terminal.
7. Switch off MICPCB.
8. Turn Halo off.
9. Turn off Ethernet switch.
10. Disconnect Ethernet cable from computer.

The Ethernet switch will then be directly connected to the VERTIGO Avionics stack to continue to test the MICPCB-VERTIGO-sensor interface with regards to data. Continued immediately from the previous test, this test will be carried out in the following steps:

1. Connect the Ethernet cable from port #5 on the switch to the Ethernet port on the VERTIGO Avionics Stack.
2. Connect the Avionics Stack to the computer via the VERTIGO dongle.
3. Turn on the Ethernet switch. Verify that the LED indicator light is on.
4. Turn on the VERTIGO Avionics Stack. Push the red reset button on the Stack if necessary. Verify that the CPU Power green indicator light is on and that the fan is turning.
5. Turn Halo on.
6. Switch on MICPCB.
7. Verify that the sensor (either ThermoCam or ORF) is being powered and that the appropriate data indicator lights (on the sensor or on the Ethernet switch) are on.
8. Verify that the laptop can receive data and view images sent by the ThermoCam/ORF.
9. Terminate data streaming from the sensor using the laptop terminal.
10. Switch off MICPCB.
11. Turn Halo off.
12. Shutdown the VERTIGO Avionics Stack from the laptop interface.
13. Turn off the VERTIGO Avionics Stack.
14. Turn off the Ethernet switch.
15. Disconnect Ethernet cable from the switch to the VERTIGO Avionics Stack.
16. Disconnect VERTIGO dongle from the computer.

6.2.5.4 MICPCB, Halo, Both Sensors, and Ethernet Switch (CL)

Verify that ThermoCam and ORF and their respective MICPCBs still function when both sensors are connected to Halo. Repeat the second half of the test (steps 1-15) in section 0.

6.2.5.5 MICPCB, Halo, a Single Sensor in Mount Structure, and Ethernet Switch (CL, KAF)

Each MICPCB now will be attached to its respective mount structure that will house the ThermoCam and ORF to verify the continued functionality of the MICPCBs.

1. Attach the MICPCB to the back plate of the mount structure.
2. While still disconnected from any other electronics, check that there are no electrical shorts between the pins and traces of the MICPCB and the aluminum mount structure.
3. Repeat steps 1-8 in section 6.2.5.1.
4. Fully assemble the mount structure cage with the MICPCB still attached to the back plate.
5. Repeat steps 2-3.
6. Attach the appropriate sensor to the mount structure.
7. Repeat the second half of the test (steps 1-15) in section 0.

6.2.5.6 MICPCB, Halo, Both Sensors in Mount Structures, and Ethernet Switch (CL, KAF)

Verify that both MICPCBs function as expected and that the same results from section 6.2.5.4 are achieved when the ThermoCam and ORF are mounted to Halo simultaneously, as shown in Figure 94.

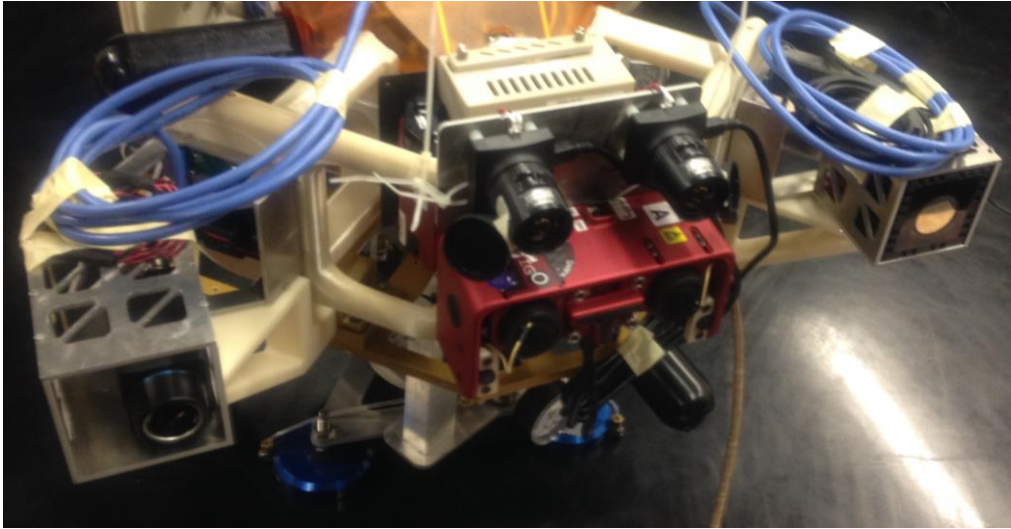


Figure 94: ThermoCam (left) and ORF (right) in their mount structures with MICPCBs connected to VERTIGO Avionics Stack, Optics Mount, and Halo. (CL)

6.2.6 CMG Full Assembly Stack Testing Capability (JS)

The CMG single component stack testing will require more structural support in order to orient SPHERES so that the Z-axis is in the horizontal plane, as required by our fully integrated testing system setup, we make use of a SPHERES-SLOSH inspired cradle, better viewed in Figure 96: Full System Testing Structure. This will allow SPHERES to rest on its side without blocking any thruster plumes. This cradle will be press fitted into the cylindrical opening on the propulsion deck or the lazy Susan bench setup as seen in Figure 88. Finally, in order to test the CMGs in the box-90 orientation we intend to use onboard INSPECT, we will use mock Halo faces as shown in Figure 85: CMG Flat Floor Single Component Testing Structure. These structures represent halo in all geometrical dimensions and will provide enough support to be a direct mount for the CMG subassembly.

6.2.7 System Level Tests (GK)

The series of system-level tests is composed of three separate tests. The first is a preliminary test involving dummy weights to symbolize the INSPECT system on an air carriage. The test evaluates translation using SPHERES thrusters and optimal pressure settings. Following completion of the preliminary test and all subsystem single component tests, an acceptance test will be done using all subsystems attached to the Halo and SPHERES. Mechanical, electronic, and data connections will be assessed and, pending compliant results, the system will be moved on to its final phase of integrated testing.

6.2.7.1 Objective

The objective of the integrated systems test is to test the concept of operations maneuvers on the flat floor of the SSL. The sensors will be taking in visual stimuli from a 2m x 0.5m test board, as the CMGs pair with SPHERES thrusters to control movement of the INSPECT system. The test board is specifically designed with a series of stimuli meant to test at, below, and above all sensor requirements for data comparison between the sensors and to actual measurements. From the analysis of the data we will be able to discern if the INSPECT system is functional and prepared for future testing inside the ISS.

6.2.7.2 Personnel

- Grace Krusell
- John Wenzel
- Alessandro Lira
- Hang Woon Lee
- James Krasner
- Melissa Kornspan
- Mic Byrne
- Matt Vernacchia
- Krystal Arroyo-Flores
- Candice Kaplan
- Connie Liu

6.2.7.3 Location

The integrated test will be completed on the SSL Flat Floor testing facility in Building 17 of MIT.

6.2.7.4 Equipment Materials

Refer to INSPECT Integrated System Test Report for full list

1. Test Board

(Refer to Figure 5)

- Topmost patterned row shall consist of the irregular shape pattern VERTIGO can recognize, and vary in depth from -5 to +5 cm, in accordance with SEN-2.
- First column on 10cm squares shall exhibit a 5cm x 5cm visual pattern, the second column 2.5cm x 2.5 cm, and third column 1cm x 1cm, in accordance with SEN-3.
- The first row of 10cm squares shall also be at a +5cm depth (juttied out from the board and closer to the INSPECT path), the second row on the board face (0cm depth), and third row at -5cm depth (realized by a square hole cut in the foam board with the visual stimuli attached at the back facing the front). This is a second iteration on the design requirement dictated by SEN-2, that allows for simultaneous check with SEN-3 (see second bullet).
- The eight aluminum plates located at the middle, bottom section of the board test for SEN-4, with alternating temperatures of either +5 degrees C or +10 degrees C. The plates also vary in size, between 3cm, 5cm, and 8 cm, which is below, at, and above requirement respectively for SEN-4. The two plates with visual stimuli attached to the aluminum will be full requirement check with a visual stimuli at requirement of 2.5cm x 2.5cm checkerboard pattern, on the face of the board (and therefore 1m away from the INSPECT sensors during maneuvers), and at 5 and 10 degrees C to test noise equivalence temperature distance.

Note: Each stimulus is subjected to truth testing prior to the test to allow verification of accuracy readings from each of the sensors.

6.2.7.5 Requirement Verification

Table 41: Integrated System Testing Requirements

Requirement ID	Requirement Description
ISS-4	The fully integrated system shall be capable of fitting in the 57.6 x 83 x 80 cm JEM airlock
S-3	The system shall not exceed a peak power draw of 55.5 watts (11.1V and 5 amps)
H-1	Each suite component shall connect to Halo using the 4-hole square screw pattern
H-2	Each suite component shall be able to connect to the Halo via USB 2.0 or Ethernet
H-3	Each suite component shall operate no more than 16.65W and be able to convert operational current/voltage from 11.1V/1.5A
H-4	The suite shall not impose a force greater than 40N in the z-direction to SPHERES
SEN-1	All imaging sensors shall have a minimum field of view of 33 degrees
SEN-2	The system shall determine the distance to a target object accurate to within 10 cm with precision to 2 cm up to 10 meters away
SEN-3	The system shall resolve a visible-light image of a 1cm per pixel image from 1 meter
SEN-4	The system shall resolve a thermal image of a 5x5 cm object from a distance of 1 meter to a +/- 5 degree C accuracy and a noise equivalence temperature difference of <1 degree C at 20 degrees C
SX-1	INSPECT shall provide a functional API for localization and mapping.
SX-2	INSPECT shall provide a functional API for identification and description of observable objects.
SX-3	INSPECT shall provide a means of assessing functionality of its components as a form of health monitoring
SX-4	INSPECT shall provide a functional API for the testing of future software
SX-5	INSPECT shall provide a platform for navigational algorithm development

6.2.7.6 Full System Testing Structure and Peripheral Support (JS)

Figure 95 shows our system as we envision it. With our peripheral subsystems weighing in at 1-2.5 kg each, INSPECT is a relatively bulky system. Given that Halo was not designed to mount heavy subsystems in the presence of gravity, the structures team was given the task of determining a structure that would fully support each peripheral, constrain the CMGs in all 3 dimensions so that all torques imparted are absorbed through the propulsion deck, and allow SPHERES to rest with its Z-axis in the horizontal plane, all while minimizing thruster plume impingement. The final outcome is shown in Figure 97.

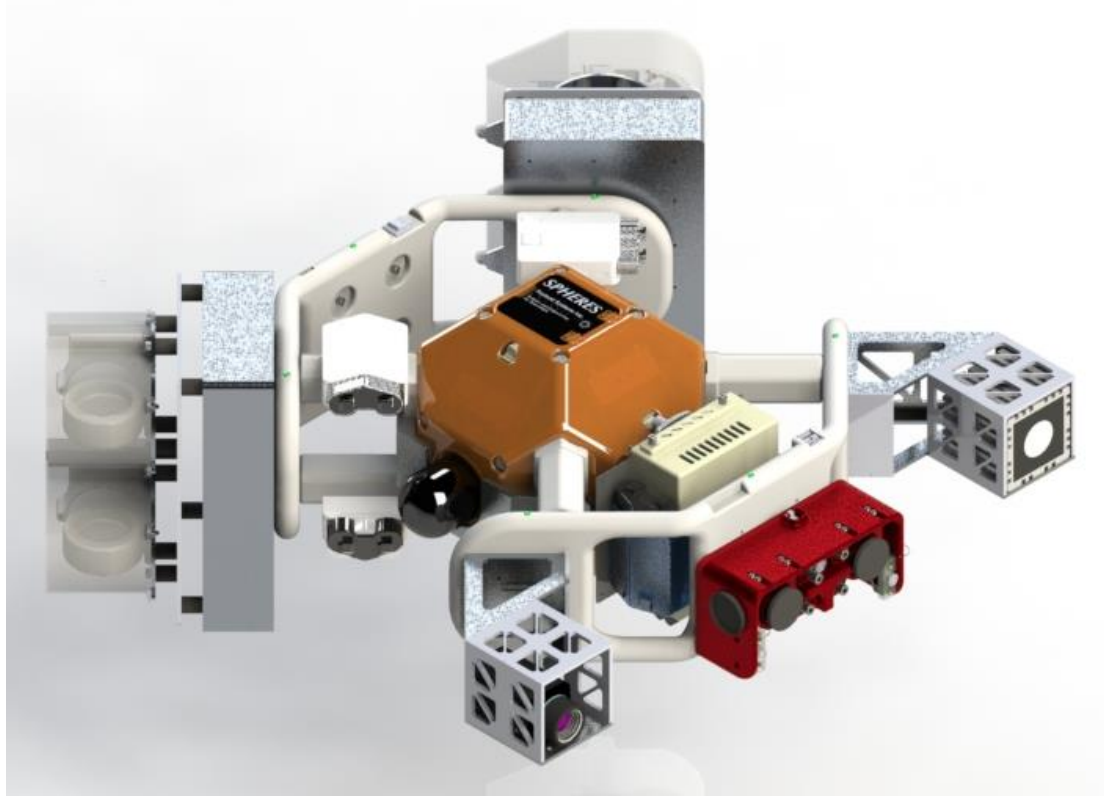


Figure 95: Inspect Without Structural Support (wiring not shown)

6.2.7.6.1 Structural Components

The testing structure will be comprised of 7 total components, 5 of which are unique, and all of which can be seen in Figure 97. The 3-puck air-carriage as well as the propulsion deck with the 4 associated 1-inch x 1-inch clamps was provided for the INSPECT team. The Cradle was 3D printed based off of an amended version of the SPHERES SLOSH project, making it press fit into the propulsion deck, and with a lighter weight and void of thruster blockage in any direction, which better fits INSPECT's testing needs. Lastly are the peripheral mounting mechanisms. There are two at the front of our system for the ORF and ThermoCam sensors. These will act purely as supports for these subsystems to ensure no loading on the Halo face. Since platform height accuracy of this setup is non trivial, these supports will be adjustable via two softheaded screws that will come up towards each of the bottom plates of our sensor mounts. The rear extremities are for our CMG subassembly. Two clamps will act as complete constraints, grabbing onto the CMG control box mounting structure as seen in Figure 96 and Figure 97. These clamps will ensure that our CMGs do not spin SPHERES out of its cradle, imparting all commanded torques through the propulsion deck and 3-puck air-carriage.

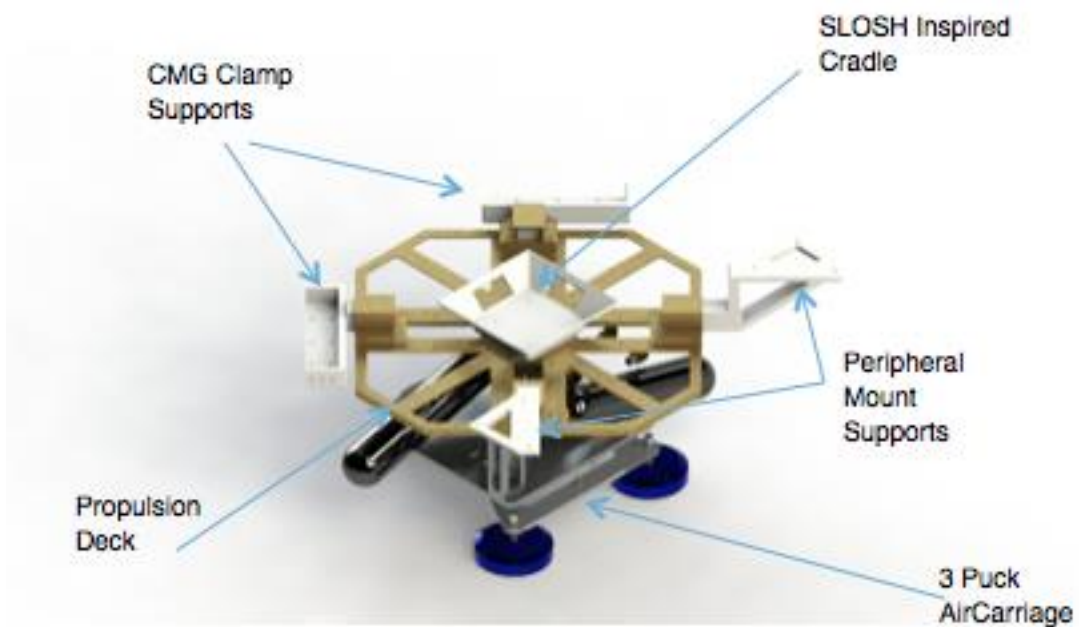


Figure 96: Full System Testing Structure

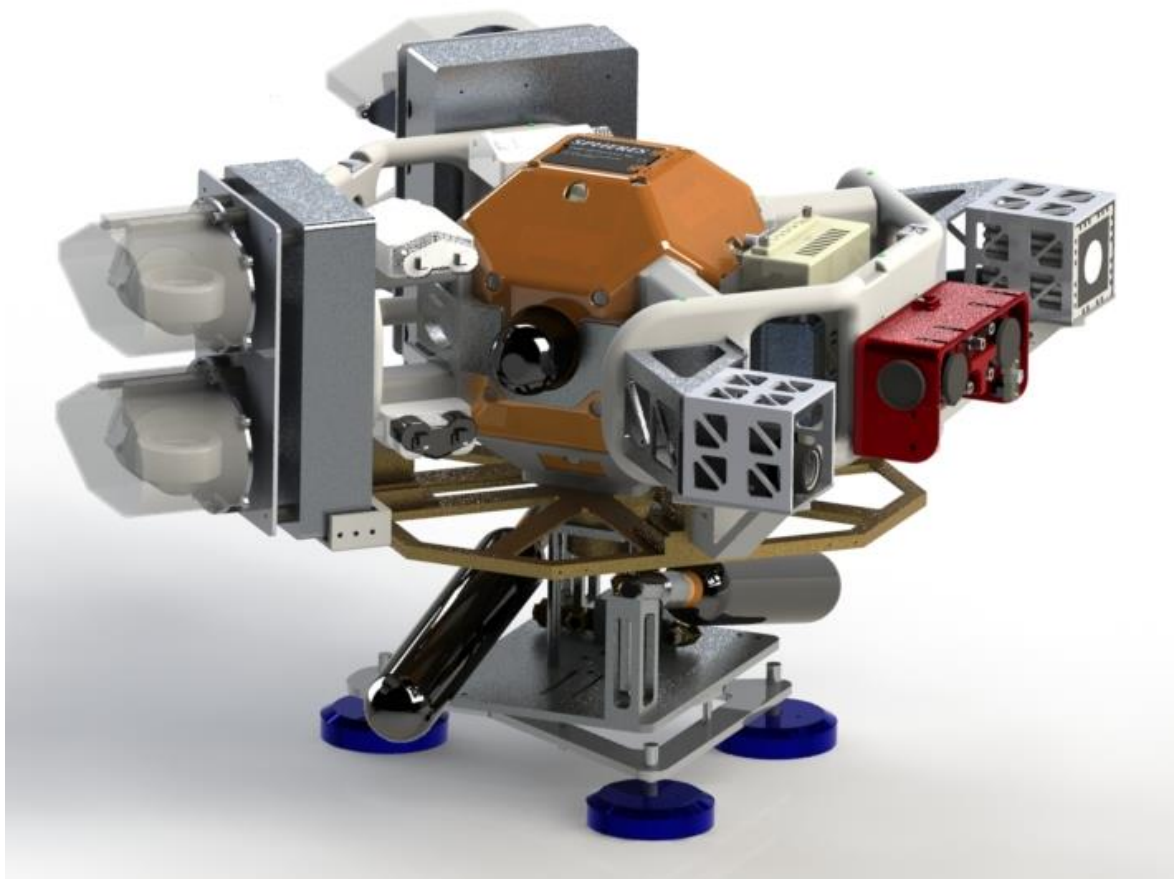


Figure 97: Fully Integrated Testing Assembly

6.2.7.6.2 Center of Mass and Volumetric Analysis

The total mass of the system, as we currently estimate, will be 26.2kg. Using solid works mass analysis tools we determine the center of mass (COM) to be displaced from the center of SPHERES by $(x,y,z) = (-18\text{mm}, 41\text{mm}, 4\text{mm})$. These coordinates correspond with our expected center of mass as it is pulled back towards the heavier CMG subsystem and down towards our testing structure. Inertia about the center of mass is approximately $.59\text{kg}\cdot\text{m}^2$ (to be verified in lab). Using the parallel axis theorem we then determined the moment of inertia about the center of SPHERES to be $1.849\text{kg}\cdot\text{m}^2$.

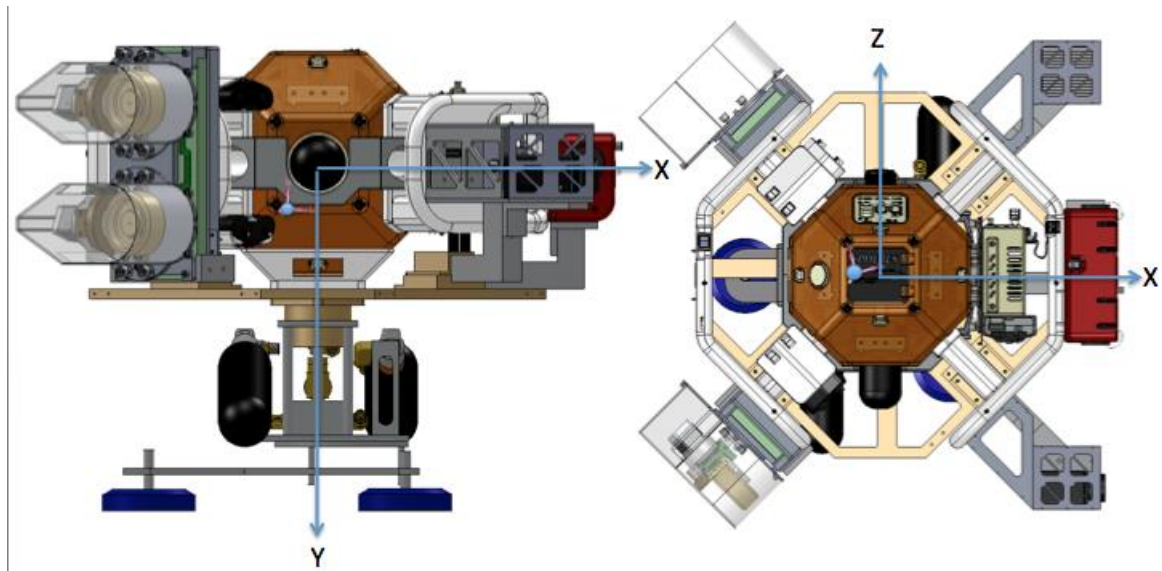


Figure 98: Fully Integrated Testing Structure COM

The volume of our full system is $575\text{mm} \times 470\text{mm} \times 630\text{mm}$ or 170257.5 cm^3 as seen in Figure 99 and Figure 100. Given the need to transport INSPECT along with its testing structure, we can cut down the volume further by reorienting individual parts after partial disassembly.

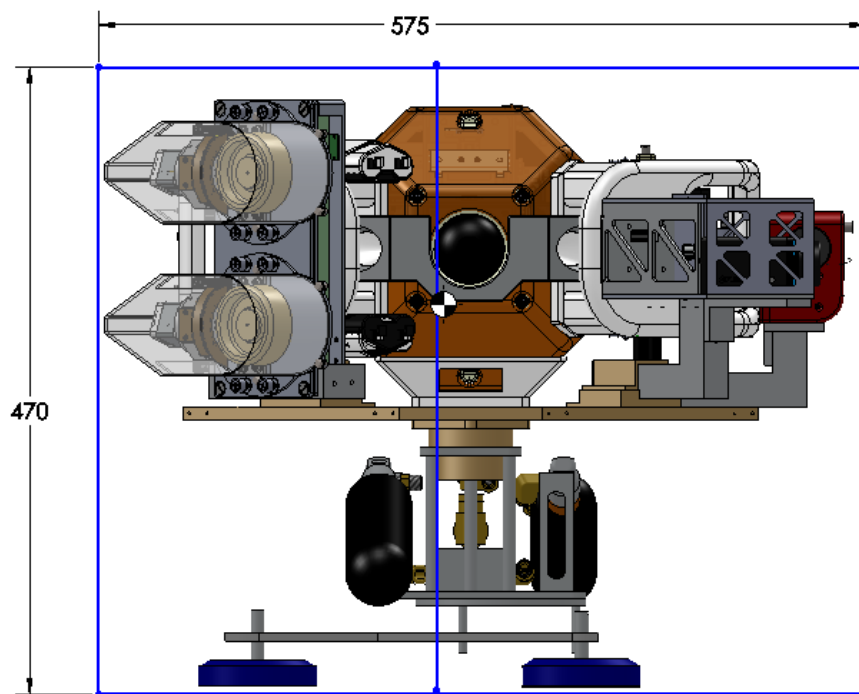


Figure 99: Profile area in x-y plane

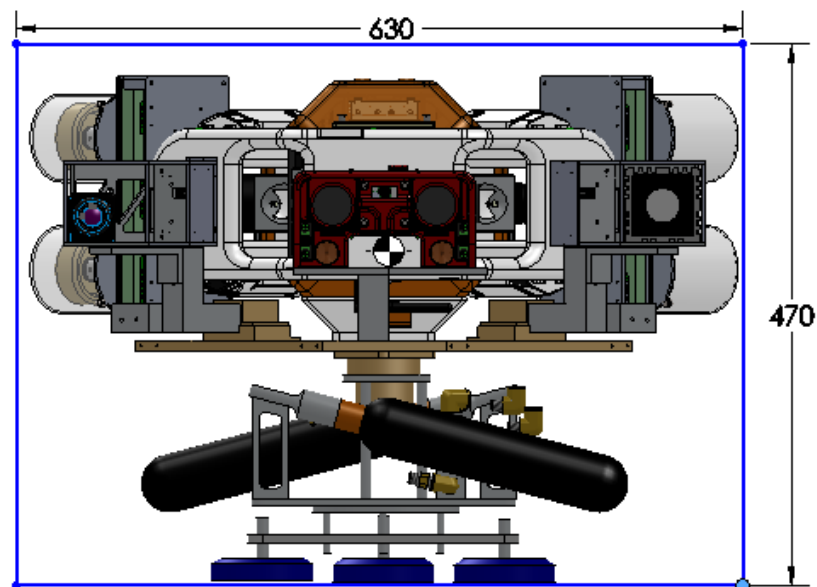


Figure 100: Profile area in y-z plane

6.2.7.7 Requirement Verification

Requirement ID	Requirement Description
ISS-1	The system shall remain inside a predetermined operational volume of the JEM (4.2 m diameter, 11.2 m length) for inside-ISS operations.
ISS-4	The fully integrated system shall be capable of fitting in the 57.6 x 83 x 80 cm JEM airlock
S-1	The system shall allow for stored information to be transferred to a host computer
H-1	Each suite component shall connect to Halo using the 4-hole square screw pattern
H-2	Each suite component shall be able to connect to the Halo via USB 2.0 or Ethernet
I-7	The sensors shall point in the same direction and be placed no more than 50cm apart
SEN-1	All imaging sensors shall have a minimum field of view of 33 degrees
SEN-2	The system shall determine the distance to a target object accurate to within 10 cm with precision to 2 cm up to 10 meters away
SEN-3	The system shall resolve a visible-light image of a 1cm per pixel image from 1 meter
SEN-4	The system shall resolve a thermal image of a 5x5 cm object from a distance of 1 meter to a +/- 5 degree C accuracy and a noise equivalence temperature difference of <1 degree C at 20 degrees C
SEN-6	The system shall be able to determine its pose in 2 dimensional space within 1 cm and 0.5 degrees with 1 axis of rotation normal to the test floor
C-1	The system shall stabilize all sensors to have a blur constant of less than or equal to 1 (see appendix for formula)
C-2	The system shall be able to translate in a controlled manner to a 1 cm accuracy
C-3	System shall be able to control its attitude through three dimensional space in a microgravity environment to 0.5 degree
C-4	System shall be capable of achieving an angular velocity of greater than 0.5 rpm but less than 9 rpm
A-1	The actuators shall provide movement for sensors that require motor functions
A-2	The system shall be capable of producing a torque of at least 4×10^{-5} Nm
A-3	The system shall be capable of linearly accelerating at 0.02 m/s^2

6.2.7.8 Test Procedure

Refer to INSPECT Integrated System Test Report for full list

1. Setup

Assemble telemetry beacons as required by the Concept of Operations (see Figure 4)

Clean flat floor (see procedure from INSPECT Acceptance Test Report)

Configure SPHERES with the testing computer and USB communicator

Place testing deck onto the air carriage and secure with clasp

Mount the SPHERES to the Halo structure (see Halo Assembly Sequence in INSPECT Integrated Test Report)

Mount and secure all subsystems in accordance with the ICD

Check communication between SPHERES and host computer

2. Procedure

Use multimeter to check voltages of all power components

Power on SPHERES and all components

Set SPHERES thruster air pressure to 35 psi
Set the air carriage pressure to 95 psi
Run code to complete Conops maneuvers (see INSPECT Integrated Test Report)

3. Timeline Summary

This test was conducted in several increments. The first took place at approximately 1300 to 1500 on May 9, 2014. The second was from 1300 to 1900 on May 10, 2014. The table below shows a summary of the tests run.

Session	Test	Description	Start Time	Interval
1	T1	SPHERE Checkout	1330	0:02
	T2	Air Carriage Checkout	1332	0:02
	T3	Integrated Test Cycle 1	1334	0:05
		Cycle 1 Adjustments	1339	0:20
	T4	Integrated Test Cycle 2	1359	0:05
		Replaces Batteries	1403	0:05
		Replaced Air Tanks	1408	0:06
		Cycle 2 Adjustments	1414	0:25
	T5	Integrated Test Cycle 3	1439	0:05
		Cycle 3 Adjustments	1444	0:06
		System Disassembly	1450	0:10
	T1	SPHERE Checkout	1330	0:02
	T2	Air Carriage Checkout	1332	0:02
	T3	Integrated Test Cycle 4	1334	0:05
		Cycle 4 Adjustments	1339	1:00
2	T4	Integrated Test Cycle 5	1439	0:05
		Replaced Batteries	1444	0:05
		Replaced Air Tanks	1445	0:06
		Cycle 5 Adjustments	1451	1:15
	T5	Integrated Test Cycle 6	1606	0:05
		Cycle 6 Adjustments	1611	0:45
	T6	Integrated Test Cycle 7	1656	0:05
		Cycle 7 Adjustments	1701	0:30
		System Disassembly	1731	0:29

6.2.7.9 Test Results

1. General

ISS-4 was verified by measuring the volume of the system. INSPECT is 0.575m by 0.470m by 0.630m, which is well within the volume of the airlock it is expected to fit through.

S-3 was verified by checking power draw from each of the components, the greatest of which was the ORF, drawing 13.36 watts which is still below the maximum component draw of 16.65 watts at each port.

2. Halo Requirement Checks

Halo physical connection was verified via inspection as all components had structural mounts designed to accommodate the 4-hole screw pattern, and all were successfully and sturdily attached. The data connection was checked via the Ethernet cables, which actually had to bypass Halo at this point and connect through an Ethernet switch to the VERTIGO avionics stack, as our current Halo prototype does not support data connection. This is expected to be resolved

for future tests. Power conversions were analyzed and checked via the interface boards to successfully convert voltage and operate safely within the power limit. Analysis for H-4 was shown to produce a 79 N force in the Z direction, which was compensated for by adding appropriate supports to the mounting structure to support Halo, thus decreasing the total force on Halo to less than 10 N. This is well below the maximum allowed 40 N force.

3. SPHERES-X Traceable Requirement Checks

Software data alignment was successful and data output was in a format compatible with the standard autonomous SLAM protocols, showing SX-2 and SX-5 to be verified. Human visible identification was also compatible with data, verifying SX-2. SX-3 is on track to be verified by the printed circuit boards for health-monitoring processes. SX-4 was verified by software successfully saving to Sata drives 10 and 11 with support for future software integration.

4. Sensor Analysis and Requirements Checks

The accuracy of the Optical Rangefinder according to the data it obtained from the test and test board is shown below.



This meets the requirement SEN-2 as the system was successfully able to determine the range to the target (the board and its varying depth stimuli) accurate to within 0.1m and precision to 0.02m. This was done at a distance 1 meter away from the board, which is within the requirement of up to 7 meters away. The error in measurement of the graph above is shown to be within the upper and lower bounds of the requirement (shown in red dashed lines), and through two different confidence intervals. Below is a second graph supporting the standard of deviation to be within acceptable values for both the requirement and vendor specifications.



SEN-1 of the ORF was verified by measured specs of 56 degrees horizontal by 70 degrees vertical for field of view, which is above the requirement of 33 degrees by 33 degrees. The VERTIGO goggles also exhibited a field of view greater than necessary as shown in the following photo.



The FLIR thermocamera measured a field of view of 47.5 degrees horizontal by 38.9 degrees vertical.

SEN-3 was verified by the VERTIGO goggles by obtaining an image of the at-requirement 1cm square pattern of the test board and successfully being able to resolve the image, as shown below.



SEN-4 was verified by the ORF as using 0.8% of the CPU and 0.3% of the RAM at 96.3 kbps of the Avionics stack. The following chart shows these values again the imaging frequency.



All are acceptable values and the requirement is verified for the ORF. By similar reasoning, the thermocam also fulfills the requirement by the chart shown below, with CPU usage of 2.1% and RAM 1.2%.



The data rate of the thermocam was 10 kbps, which is shown below and is at a rate that can be processed by the Avionics stack so no external computer is necessary for processing and the requirement is verified.



The thermocamera was able to resolve a thermal image from the thermal pads on the test board from 1 meter away to ± 5 degrees Celsius accuracy and less than 1 degree precision, verifying SEN-5. Below shows the images the thermocam recorded of the test board.



1 and 3 dictate the at-requirement 5cm by 5cm plates, and 2 and 4 are the above-requirement 4cm by 4cm plates.



The above chart shows the measured values from the thermocouple versus the error of the measurement from the sensor. All values are within the upper and lower bounds of the requirement.



The standard deviation shows to be within 0.25 and 0.35, which is within precision limits.

6.2.7.10 Future Testing

INSPECT is now prepared for more intensive integrated testing on its way to becoming SPHERES-X, including a possible testing session in the reduced gravity aircraft (RGA). All of the requirements up to this point have been verified or are on track to be verified.

7 Conclusion (MC, HS, MK)

INSPECT, with its modular design utilizing the Halo structure, rangefinding and thermal imaging capabilities, and OpenCV compatibility, is a solid first step forward towards the NASA HEOMD vision of free-flying autonomous vehicles that can inspect, navigate, and characterize in an extravehicular space environment. INSPECT aims to demonstrate these capabilities in an Earth-based laboratory environment, with the project eventually moving to testing on a Reduced Gravity Aircraft and then on the International Space Station (inside and then eventually outside) itself. At its current stage in development, INSPECT fulfills project budget allocations in terms of mass, average power, peak power, data rate, data processing, and cost. The current preliminary prototype can be found in the MIT Space Systems Laboratory, with continued development on-track to continue at least through summer 2014.

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10 Appendix A: Contact Information

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11 Appendix B: Subsystem Tradespaces

11.1 Optical Rangefinder (MV)

To reach this decision, the type of optical range finding sensor to be used was considered. The following Optical Rangefinder types are commonly used in the robotic navigation community and were considered for use in INSPECT:

Table 43: Rangefinder Technology Comparison

Sensor Class	Model considered for inspect	Typical Cost [USD]	Typical Max. Range [m]	Scanning Structure	Works in direct sunlight?	Other
LIDAR / 2D scanning	Hokuyo UTM-30LX	3 000	30	2D	Yes	Laser safety
LIDAR / 2D scanning multi-beam	None, too expensive	30 000	30	3D	Yes	Laser safety
LIDAR / 3D scanning	None, too expensive	90 000	30 to 2 000	3D	Yes	Laser safety
LIDAR / 3D flash	None, too expensive	100 000	30 to 500	3D	Yes	Limited laser life, Laser safety
Laser triangulation rangefinder	None, range to short	200 to 10 000	2	1D, 2D or 3D	Yes	Laser safety
Phase shift time of flight camera	MESA SR4000, MESA SR4500	4 000	10	3D	No	
Structured light	None, range to short	200	4	3D	No	

The Hokuyo UTM-30LX, MESA SR4000, and MESA SR4500 were identified as feasible sensors. Next, a trade study was performed between these sensors to identify the option which best matched our mission requirements.

Table 44: Optical Rangefinder candidate specifications



	MESA SR4000 (Phase ToF)	MESA SR4500 (Phase ToF)	Hokuyo UTM-30LX (2D scan LiDAR)
Avg / Peak power [W]	9.6 / 12	12 / 120	8.4 / 12
Mass [kg]	0.510	0.850	0.370
Dimensions [cm]	6.5 x 6.5 x 6.8	11.9 x 7.5 x 6.9	6.0 x 8.7 x 6.0
Cost [USD]	4279	4849	5600
Angular range [deg]	69x56	69x56	120
Angular resolution [deg]	0.39	0.39	0.25
Distance range [m]	10	9	30
Distance resolution [mm]	15	40	50
Scan time [millisec]	20	33	25
Light wavelength [nm]	850	850	905
Works in bright light?	No	Yes	Yes
Data connection	USB or Ethernet	Ethernet	USB or Ethernet
Data rate [Mbit/s]	4 to 40	4 to 40	1

Table 45: Optical Rangefinder Pugh Chart

Feature	Feat. Priority	MESA SR4000	MESA SR4500	Hokuyo
Meets Halo power constraint	3	Yes		Yes
3D scan w/o gimbal	2	Yes	Yes	
Sunlight operation	1		Yes	Yes
	Total Score:	5	3	4

Meeting the Halo power constraint is a high priority, as failure to meet this constraint would necessitate a re-design of the Halo power supply or other intervening measures. 3D scanning without a gimbal is a medium priority, as gimbaling the sensor increases design complexity and

makes attitude control more difficult. Sunlight operation is a low priority, as only artificial lighting is present inside the ISS. None of these sensors meets outgassing/thermal/radiation requirements for operation outside of station. As such, different sensors will be required for SPHERES-X.

11.2 Thermographic Camera (TW)

The Thermographic Camera chosen was the FLIR A5. This decision was reached by comparing the cameras in Table 46 using the trade space summarized in Table 47.

Table 46: Thermographic Cameras Candidate Specifications

Model	Mass (kg)	Power	Volume (cm ³)	Cost	Field of View	Resolution	Thermal Sensitivity	Thermal Range
Omega OSXL-I7	0.363	-	1521	\$1,995	29° x 29°	140 x 140	0.1°C	-20–250 °C
Omega OSXL-E30	0.826	-	1350	\$1,995	29° x 19°	160 x 120	0.07°C	-20–650 °C
Mikron Thermo Tracer 7302	1.18	12V at 5W	1817	-	29° x 22°	320 x 240	-	-40–500 °C
MC320L	1.16	12-30V at 7W average 13W max	1211	-	52.6° x 39.7°	320 x 240	0.06°C	-40–120 °C
FLIR A5	0.2	12/24 VDC at 2.5 W max	187	\$2,300	44° x 36°	80 x 64	0.05°C	-40–160 °C

Table 47: Thermographic Camera Tradespace

	Cost (5)	Mass (5)	Volume (5)	Field of View (4)	Power (4)	Thermal Sensitivity (3)	Thermal Range (2)	Resolution (1)	Total Score
Omega OSXL-I7	3	4	4	2	-	1	2	2	72
Omega OSXL-E30	3	2	1	1	-	3	5	3	56
Mikron Thermo Tracer 7302	-	1	3	1	2	-	4	5	45
MC320L	-	1	4	5	1	4	1	5	68

FLIR A5	2	5	5	4	5	5	1	1	114
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Each item is rated on a scale of 1-5 for each category, which is then multiplied by the weighting factor indicated in the header row and summed to determine a final score. The FLIR A5 received the largest score by a 42-point lead.

11.3 ADCS (LJ)

The attitude determination and control system (ADCS) chosen was the Honeybee CMGs. This decision was reached by comparing the actuators in Table 48 using the tradespace summarized in Table 49.

Table 48: Actuator Candidate Specifications

Actuator	Actuator Type	Mass [kg]	Max Control Moment [N-m]	Max Angular Momentum [N-m-s]	Dimensions [cm]	Average Power [W]	Max Power Needed [W]	Cost [USD]
Honeybee CMGs	CMG	3	0.112	0.056	23x12.5x8.2	10	14	0
Maryland Aerospace	Reaction Wheel	0.64	0.000635	0.0011	8.1x8.1x6.9	4	7.2	12745
RW-0.01	Reaction Wheel	0.12	0.01	0.01	5x5x3	0.16	0.7	20000
RW-0.03	Reaction Wheel	0.19	0.03	0.03	5x5x4	0.4	1.5	25000
RW-0.06	Reaction Wheel	0.23	0.06	0.06	7.5x6.5x3.8	0.5	7	35000
Clydespace	Reaction Wheel	1.5	0.035	1.9	13.5x13.5x8.2	-	28	33000
Clydespace	3 x Magnetorquer	0.15	3.42E-05	N/A	10x10x.43	2	6	4800
SSBV	3 x Magnetorquer (20 cm)	3.3	0.006	N/A	20 (each)	3	3	4500
AraMiS ADCS	Reaction Wheel	0.57	0.253	0.03519	Tiny	8	8	14000

Table 49: Attitude Control System Pugh Chart

	Mass [10]	Power [20]	Cost [35]	Control Authority [15]	Limitations [Multiplier]	Total

Honeybee CMGs	0.626	0.405	0	0	1.167	16.76
Maryland Aerospace rx wheels	0.133	0.208	0.208	0.561	47.24	1002
RW-0.01	0.025	0.020	0.327	0.382	3	53
RW-0.03	0.039	0.043	0.409	0	2.083	32.42
RW-0.06	0.047	0.202	0.572	0	2.917	71.61
Clydespace	0.313	0.811	0.540	0	2.75	105.1
3 Clydespace z-axis	0.031	0.174	0.078	0.573	877.2	13270
SSBV	0.688	0.087	0.074	0.459	5	90.38
AraMiS ADCS	0.119	0.232	0.229	0	1.167	16.14

Table 49, the magnitude of the mass, power, cost and control authority have been normalized and then multiplied by a factor based on the worst parameter ratio compared to the respective budget. Note that AraMiS ADCS would have to be less than \$14000, making it an unlikely candidate. Based on the tradespace above, the Honeybees CMG were chosen.

12 Appendix C (KH)

This section lists the payloads which we have chosen not to use on the final version of INSPECT. For each not-selected payload, the following information is provided:

1. Purpose/relevance to INSPECT
2. Driving requirements
3. Trade study
4. Justification as to why it is not a part of the system
5. How it can be incorporated if desired

12.1 Radio/GPS (GP)

12.1.1 Purpose and Relevance to INSPECT (GP)

GPS allows for the localization of a SPHERES in free space and the subsequent navigation relative to ISS.

12.1.2 Requirements Satisfied (GP)

ID	Requirement	Parent	Rationale	Verification
SX-1	The system shall provide a functional API for localization and mapping.	M-1	Needed to fulfill mission goal properly test the system	Testing
SEN-2	The system shall determine the distance to a target object accurate to within 10 cm with precision to 2 cm up to 10 meters away	SX-1, SX-2	Defines ranging limits	Testing

12.1.3 Trade Study

Since GPS signals can not be received within the ISS because the GPS constellation is not visible from inside, the use of GPS on INSPECT for the purpose of testing is more complex than any other sensor choice. Simulated GPS signals would have to be used to test within the ISS. It is important to note what the capabilities of GPS as a navigation tool were, as all simulation techniques would revolve around the capabilities of GPS after receiving GPS data and determining position.

Possible options were to send up pseudolites to act as satellites or to use the existing metrology system on SPHERES as a pseudo GPS. Of the two options the latter would be the option of choice since it makes use of existing and well tested systems.

In order to examine whether the acoustic metrology system on SPHERES would function as a testing double of GPS, the capabilities of the two systems would need to be contrasted. Specifically the positioning accuracy of the acoustic metrology system needs to be compared with that of GPS.

Baseline Component	Estimation Error	
	Max, cm.	RMS, cm.
Magnitude ($ B $)	35.8	4.2
Along Track (B_x)	36.9	4.5
Cross Track (B_y)	28.0	2.4
Radial (B_z)	91.2	6.8
Kin. Correction Availability	96.3 %	
Ambiguity	IA Estimation	
	Fixing Rate, %	Fail Rate, %
WL ambiguities	98.0	0.0
L1 ambiguities	98.0	3.6

Table of relative navigation performances of LEO Carrier-based Differential GPS [17]

Based on the table of relative navigation performances of in-orbit GPS we observe relatively large maximum estimation errors compared to the current metrology system currently on SPHERES. As such, a direct one-to-one substitution for the purpose of testing would not provide accurate results nor the appropriate risk mitigation desired. Adaptations that would have to be made to the ultra sound metrology system in place are discussed in 12.1.4 (inclusion on INSPECT) and 12.1.5 (inclusion on SPHERES-X).

12.1.4 Decision Made (GP)

It was decided not to include a GPS on INSPECT due to the difficulty of testing inside the ISS. It is recommended that such a system be used for SPHERES-X in the future as a means of navigation and localization. Based on the trade study comparing in-orbit GPS positioning accuracy to what can be currently be obtained by the acoustic metrology system, it is determined that we can simulate the use of in orbit GPS by inducing an error to the metrology data.

Specifically we observe across all tests, a max error of roughly 30 cm with a RMS error of 4 cm. A probability distribution which accurately encapsulates said properties can be used to draw samples from, and subsequently add to the metrology data to simulate and therefore test the capabilities of in-orbit GPS. This would allow us to use the existing acoustic system as a proof-of-concept substitute in place of GPS.

12.1.5 Incorporation (GP)

To include GPS what would be required is the following:

Hardware:

- Antenna capable of receiving GPS signals
- Hardware filter able to handle Doppler shift and isolate proper frequencies

Software:

- Software for time of flight calculations to determine position
- Extended Kalman Filter for state estimation from received signals

Both of these pieces of software are already built into the SPHERES computer as they are used to correctly estimate their state using metrology data. Additional software can be included to mitigate the effect of errors caused by distortions from the ionosphere. Furthermore more advanced carrier-based differential techniques could be used to improve accuracy.

The GPS would likely be made internal to SPHERES-X, hence not requiring power from Halo. Along the same vein, the GPS hardware would not mount to a Halo port and would use the

SHERES-X computer for calculations, hence being disjoint from the VERTIGO computer and the timing constraints it imposes.

12.2 Hazcams (HS, KH)

12.2.1 Purpose and Relevance to INSPECT

Hazard Avoidance Cameras (Hazcams) will be used to avoid collision with other objects (primarily the ISS) when a SPHERES is in a tightly confined area.

12.2.2 Requirements Satisfied

ID	Requirement	Parent	Rationale	Verification
ISS-5	The system shall not be a hazard on the ISS.	M-2	Safety is key for mission risk reduction	Testing
H-2	Each suite component shall be able to connect to the Halo via USB 2.0 or Ethernet	S-4	SPHERES will be utilized as the foundation for the sensor/actuator suite	Testing
H-3	Each suite component shall operate on a 11.1 volt, 5 amp power supply	S-4	Halo power settings	Analysis

12.2.3 Trade Study

Table 50: Hazcam Tradespaces

Model	Avg. Power	Diagonal Field of View	Cost	Mass	Volume	Frames/sec	Resolution
IDS uEye LE	0.65 W	70.7°	\$200	0.012 kg	0.036 x 0.036 x 0.020 m ³	15	5 M
Lifecam Cinema	2.5 W	73.0°	\$70	0.0953 kg	0.056 x 0.046 x 0.040 m ³	30	5 M
Logitech B910	2.5 W	89.5°	\$80	0.080 kg	0.096 x 0.034 x 0.080 m ³	30	5 M

12.2.4 Decision Made

The decision was made to not include a visual hazcam system for several reasons. First, the amount of data collected by these cameras was deemed too high for the purpose that they serve, and slowing down the data collection and processing rate to accommodate this limitation would slow down the entire system significantly. These cameras normally collect at frame rates of 5-60 FPS, and return frames of up to 5 megapixels. Even if the frame rate was slowed more and the image resolution decreased, the processing of these images would require a human observer to constantly check on the images to ensure that no hazards were present. As such, proximity sensors were determined to be a better type of sensor to fulfil the requirements that hazcams were geared towards.

12.2.5 Incorporation

If incorporated, multiple (3-5) hazcams would clip on to Halo. They would be pointed in different directions to give as much of a visual field of view as possible. Power and data interface would both be through USB 2.0 (all cameras in the trade study had this capability, though due to the port limitations on Halo, the cameras would have to share a single Halo port using a USB splitter). Some cameras have embedded software to change image quality in different ways, so image quality and frame rate would be adjusted to meet data and human inspection requirements. Lighting will be a major limitation for the hazcams. Unless an additional lighting system similar to the VERTIGO strobe lights is incorporated, these cameras would be largely useless for periods when adequate lighting is not available.

12.3 Proximity Sensors (KH)

12.3.1 Purpose and Relevance to INSPECT

Proximity Sensors will be used to avoid collision with other objects (primarily the ISS) when a SPHERES is in a tightly confined area.

12.3.2 Requirements Satisfied

ID	Requirement	Parent	Rationale	Verification
ISS-5	The system shall not be a hazard on the ISS.	M-2	Safety is key for mission risk reduction	Testing
H-2	Each suite component shall be able to connect to the Halo via USB 2.0 or Ethernet	S-4	SPHERES will be utilized as the foundation for the sensor/actuator suite	Testing
H-3	Each suite component shall operate on a 11.1 volt, 5 amp power supply	S-4	Halo power settings	Analysis

12.3.3 Trade Study

Model	USB-ProxSonar-EZ	Sharp GP2Y0A02 Optical Sensor	Sharp GP2Y0A710K0F Optical Sensor	SICK DL35-B15552
Avg. Power	0.015 W	0.165 W	0.150 W	1.7 W
Cost	\$50	\$15	\$27	(need quote)
Mass	0.0049 kg	0.0048 kg	0.0050 kg	0.065 kg
Volume	0.610" x 0.863" x 0.888"	1.16" x 0.51" x 0.85"	2.28" x 0.67" x 0.89	1.68" x 2.80" x 1.26"
Min Range	6"	8"	40"	8"
Max Range	125"	60"	216"	1400"
Response Time	-	38 ± 10 ms	17 ± 4 ms	1 ms
Interface	USB	3-pin JST	5-pin JST	5-pin M12

12.3.4 Decision Made

The decision was made to not include proximity sensors because the updated requirements only specify that the front of the SPHERES should maintain a minimum distance from all obstacles. Both the VERTIGO Optics Mount and the Optical Rangefinder (ORF) are able to be used to meet this requirement; thus proximity sensors will not be used.

12.3.5 Incorporation

If incorporated, multiple (3-5) proximity sensors would clip on to Halo. They would be pointed in different directions to detect obstacles in as many different directions as possible. Power and data interface would both be through USB 2.0 (some proximity sensors would have to have custom-made interfaces that would allow them to connect to a USB 2.0 port). Unlike for hazcams, lighting would not be a limitation for proximity sensors as they can operate in the dark.

13 Appendix D: Halo Interface Board Layouts (CK, CL)

13.1 Unified PCB Iterations (CK)

It should be noted that not every iteration of the MICPCB designed is posted below. This is largely due to problems within the Eagle CAD iterations of the MICPCB, and multiple changes happening in each new version, cause some versions to not be saved. For these reasons, versions 15 and 16 are not posted below. Additionally, the MICPCB versions used for testing and designed for the next iteration (v18 and v19) are not posted below because they can be seen in section 1.1.1.1. as Figure 35 and Figure 37. No versions of the PCB that were not unified are posted in this document, because it was decided early in the design process to design a board to power both the ORF and ThermoCam sensors; individual PCBs for each sensor are not relevant to this paper. The PCB versions are in chronological order in terms of version numbering; versions 1 through 17 of the unified/multiple interface connector (MIC) boards can be seen in the figures below. (CK)

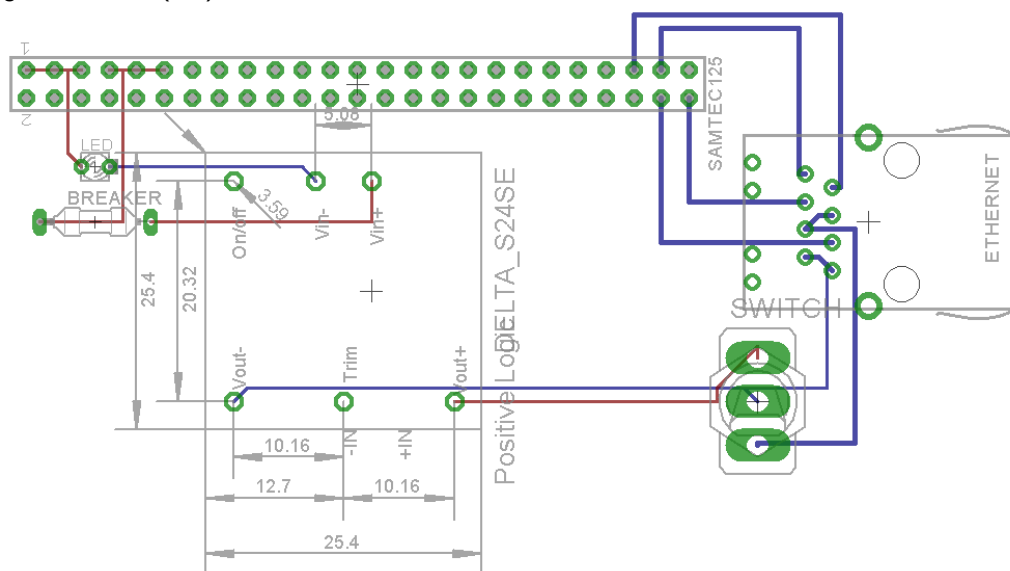


Figure 101: Unified Printed Circuit Board v1 (JB, CK)

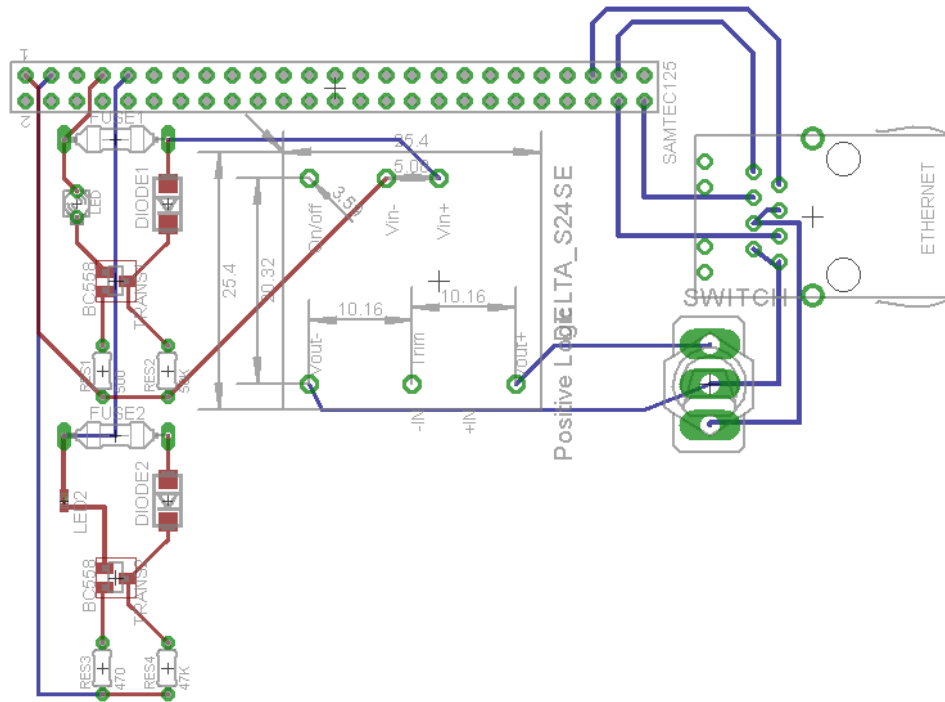


Figure 102: Unified Printed Circuit Board v2 (JB, CK)

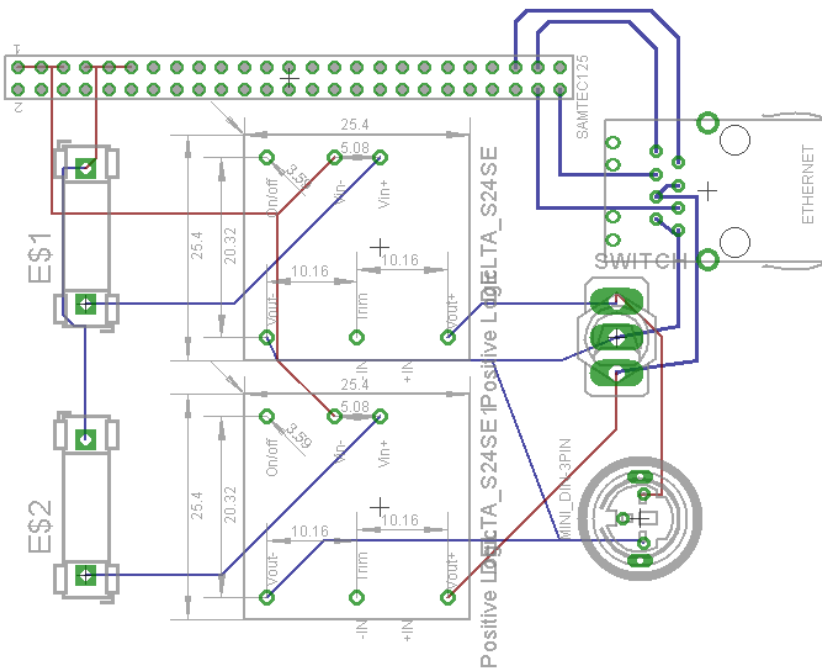


Figure 103: Unified Printed Circuit Board v3 (JB, CK)

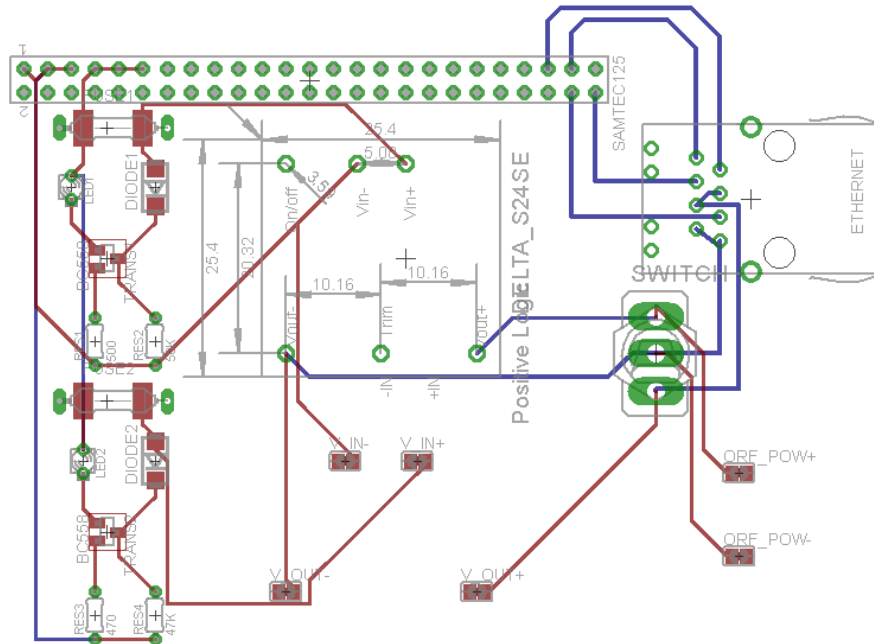


Figure 104: Unified Print Circuit Board v4 (JB, CK)

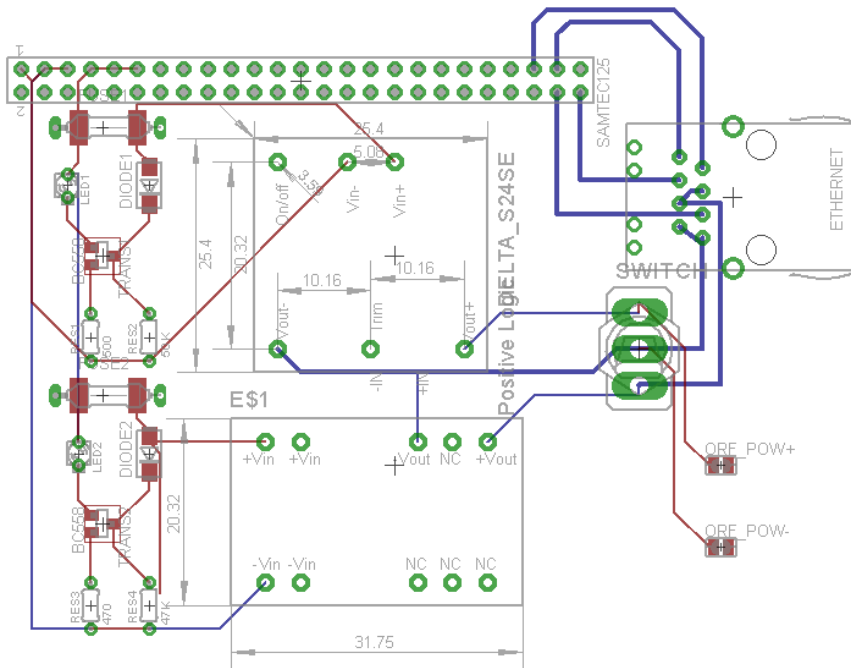


Figure 105: Unified Print Circuit Board v5 (JB, CK)

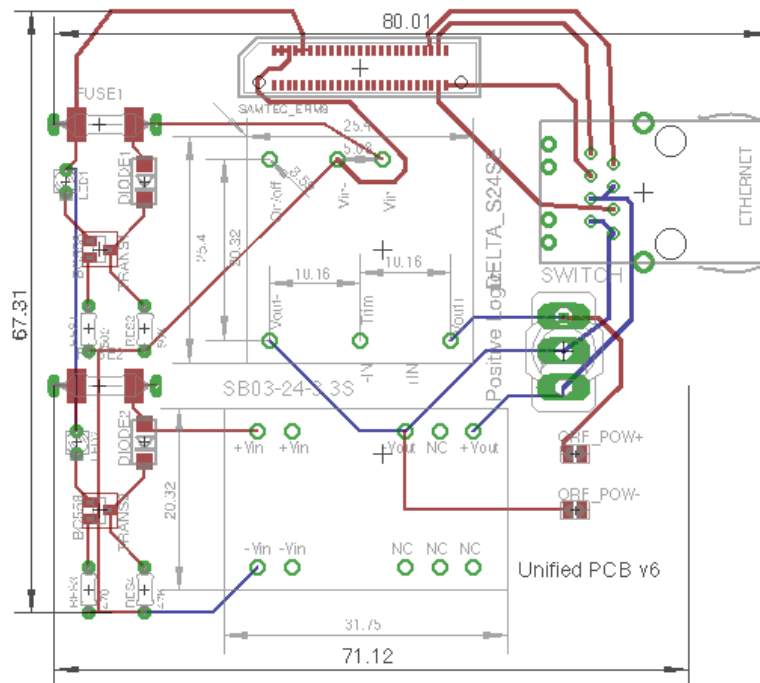


Figure 106: Multiple Interface Connector (MIC) Printed Circuit Board v6 (CL, NM)

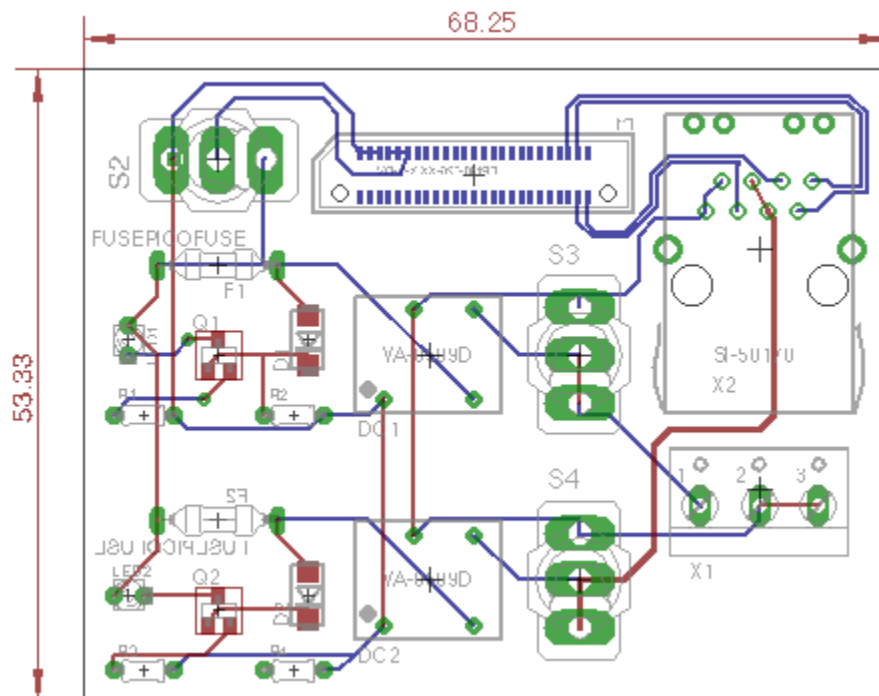


Figure 107: Multiple Interface Connector (MIC) Printed Circuit Board v7 (CL)

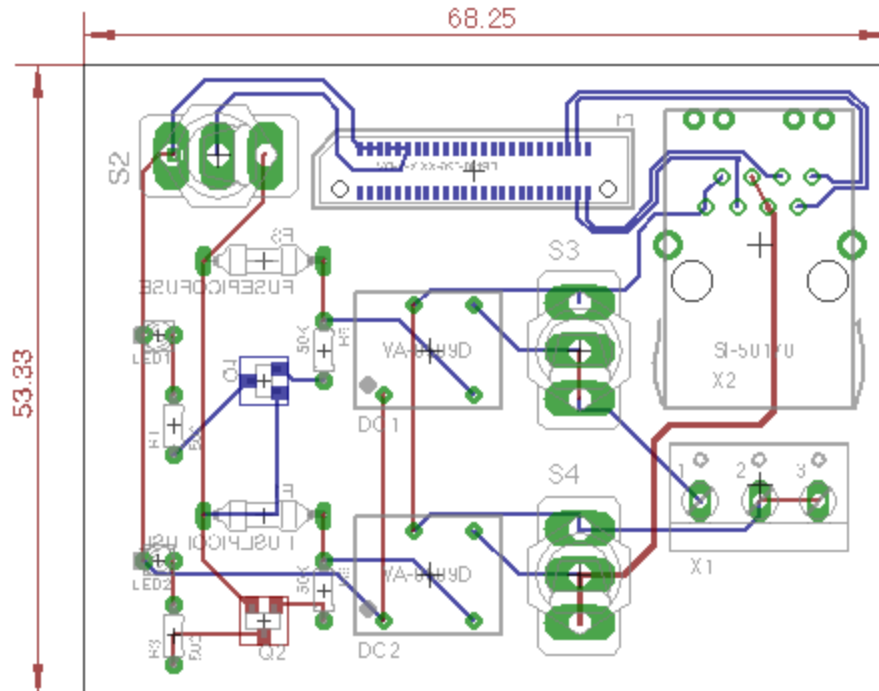


Figure 108: Multiple Interface Connector (MIC) Printed Circuit Board v8 (CL)

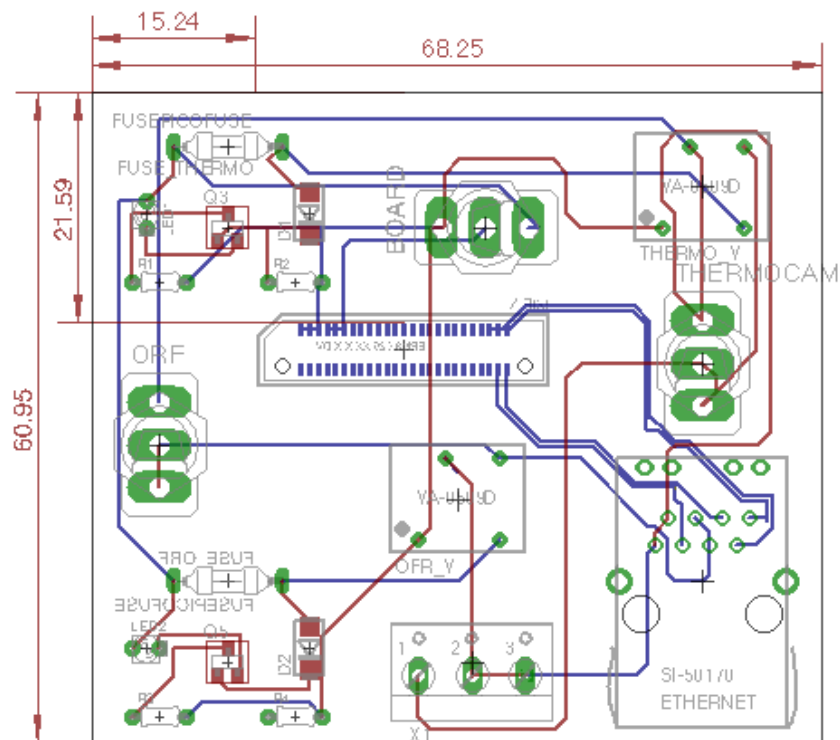


Figure 109: Multiple Interface Connector (MIC) Printed Circuit Board v9 (CL)

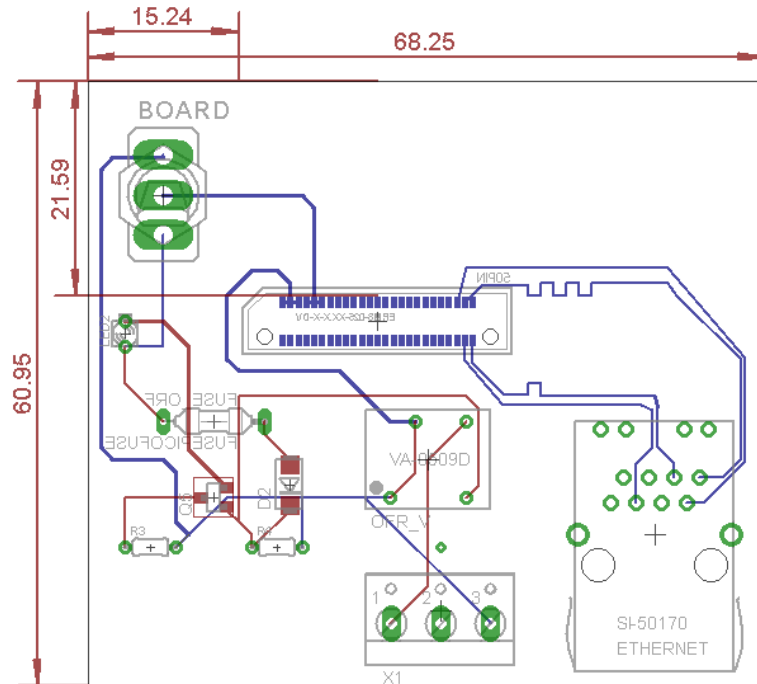


Figure 110. Multiple Interface Connector (MIC) Printed Circuit Board v10 (CK,CL,GP)

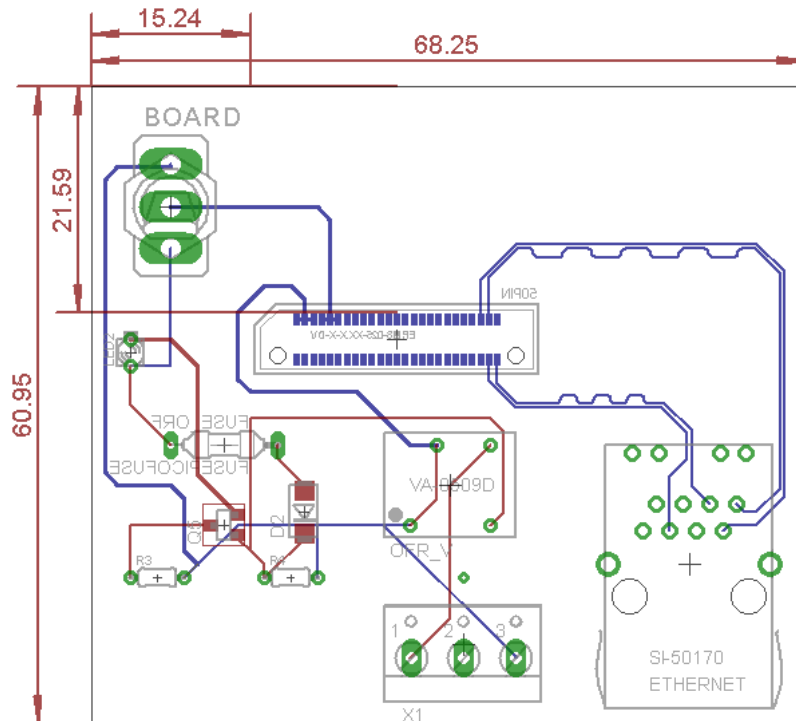
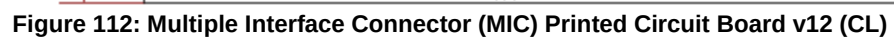


Figure 111: Multiple Interface Connector (MIC) Printed Circuit Board v12 (CK,CL,GP)



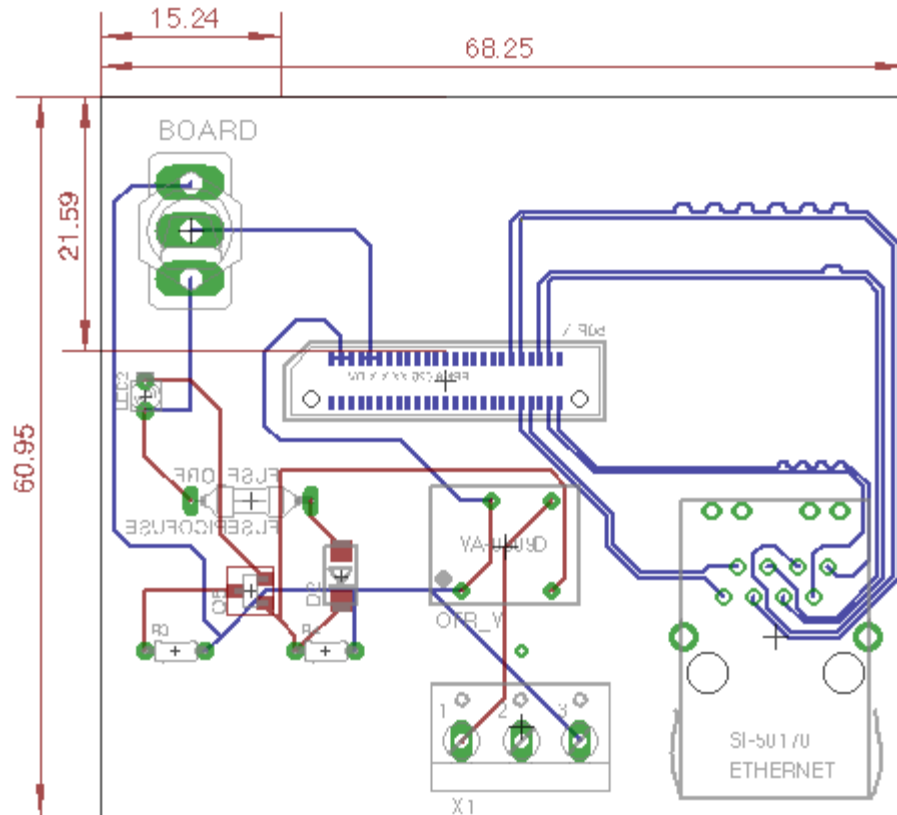
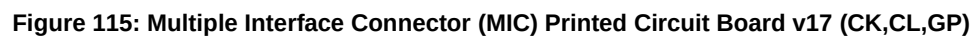
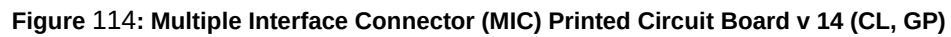


Figure 113: Multiple Interface Connector (MIC) Printed Circuit Board v13 (CL, GP)



13.2 Custom Eagle CAD Parts (CK)

Throughout the design of the MICPCBs, several essential parts were found that lacked an Eagle CAD library. This required custom Eagle CADs to be made for specific parts that were necessary to route power and data through the MICPCBs. Specifically, the voltage regulator, screw terminal, and Ethernet connector on both the tested and integrated MICPCB and the planned health-monitoring MICPCB lack accessible Eagle CAD representations. The S24SE12002PDF A DC-DC voltage regulator and the SS-7188V-A-NF 8-pin Ethernet connector both had reliable data sheets, so their respective CAD libraries were created from the data sheet specifications. The 1771101PHEONIX screw terminal did not have a reliable data sheet, so measurements were taken in the lab in order to present a footprint of the screw terminal in Eagle CAD. All of these components' Eagle schematic and board layout representations can be seen in the below figures, with the schematic symbol on the left of the figure, and the layout footprint on the right of the figure. These CAD libraries will be useful for further MICPCB development and testing as all three parts were essential and consistent during integration and testing.

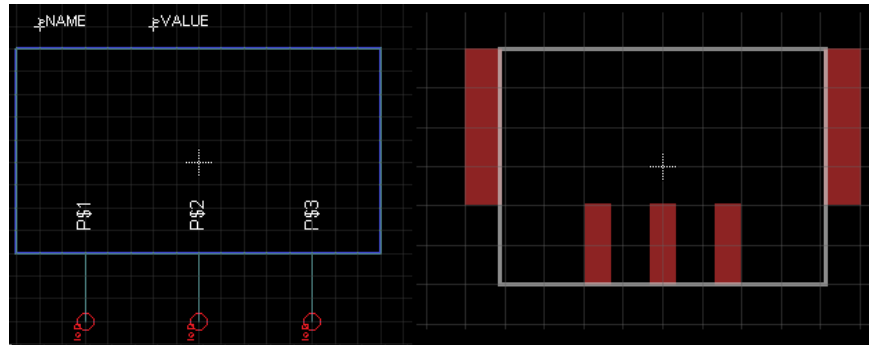


Figure 116. Screw terminal used on the MIC PCB custom Eagle CAD (1771101PHEONIX) (CK)

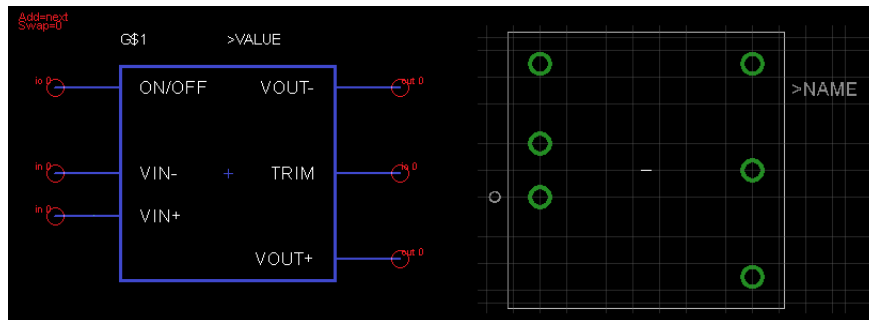


Figure 117. Voltage regulator used on the MIC PCB custom Eagle CAD (S24SE12002PDF A) (CK)

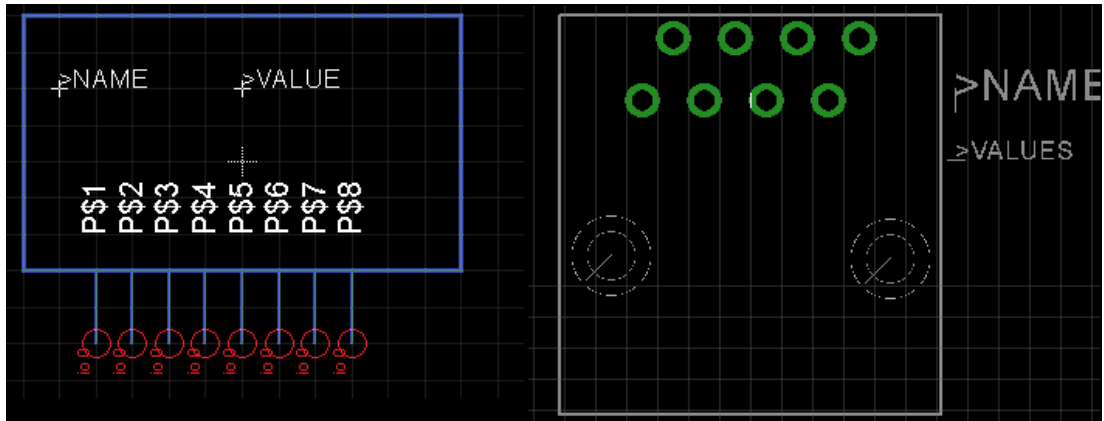


Figure 118. Ethernet connector used on the MIC PCB custom Eagle CAD (SS-7188V-A-NF) (CK)

13.3 CMG PCB Schematic

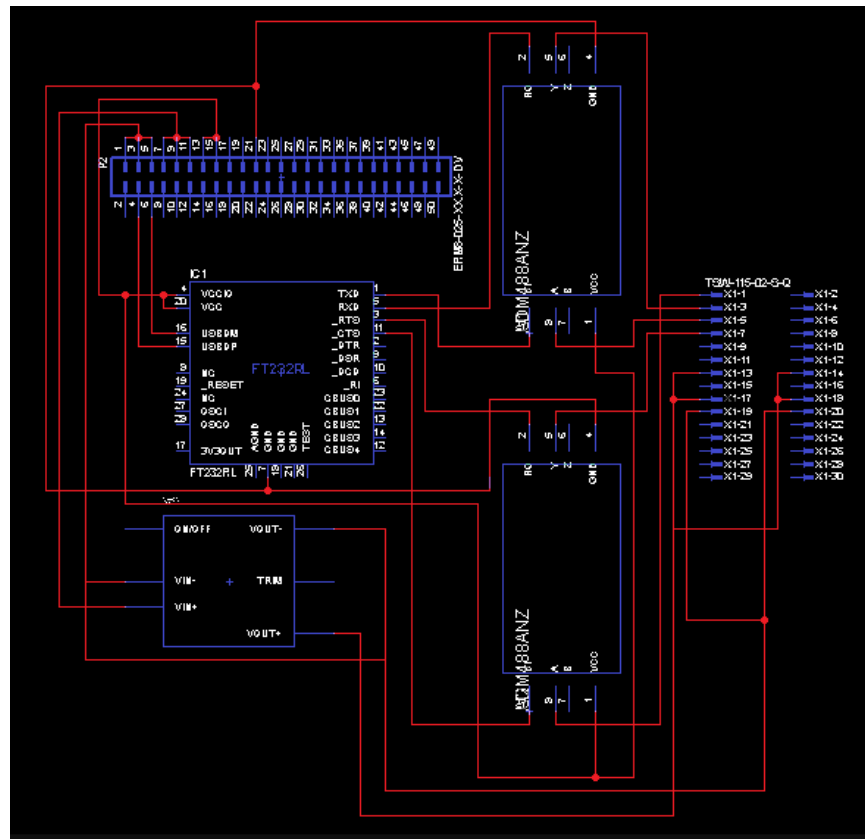


Figure 119: Printed Circuit Board for the CMGs, schematic (NM, GP, CK)

14 Appendix E: CAD Overview (MK)

14.1 Integrated Assembly

There are several existing INSPECT system CAD assemblies, each representing different layers of the SPHERES-INSPECT platform. Figure 120 pictures all assembled subsystems including SPHERES, VERTIGO, Halo, and the INSPECT sensor suite components on their respective Halo ports. Note that components are depicted without wiring.

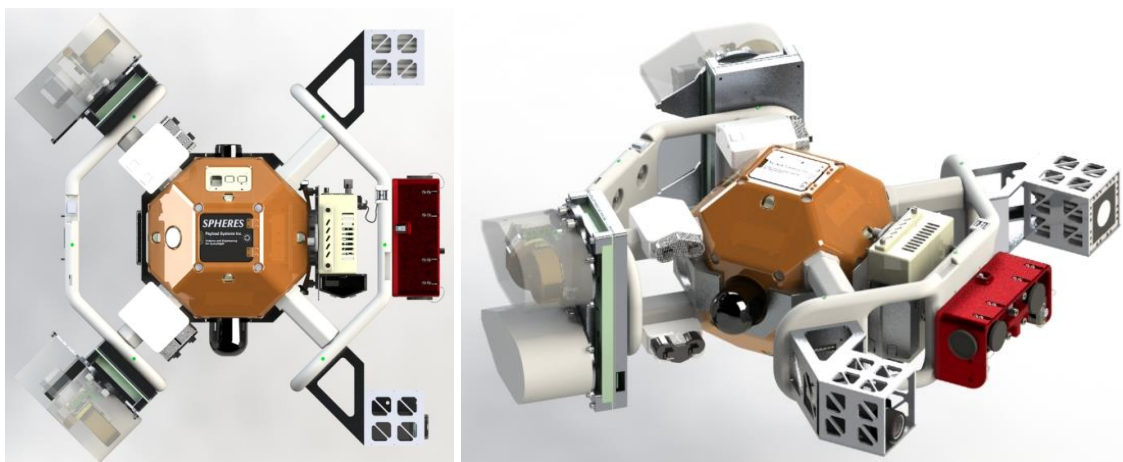


Figure 120 (a) and (b): Integrated INSPECT Assembly with Side View

14.2 Subassemblies [4]

The base platform for INSPECT is the SPHERES testbed, pictured in Figure 121 below. The distance from the $-X$ face to the rightmost edge of the expansion port is 22.5 cm.

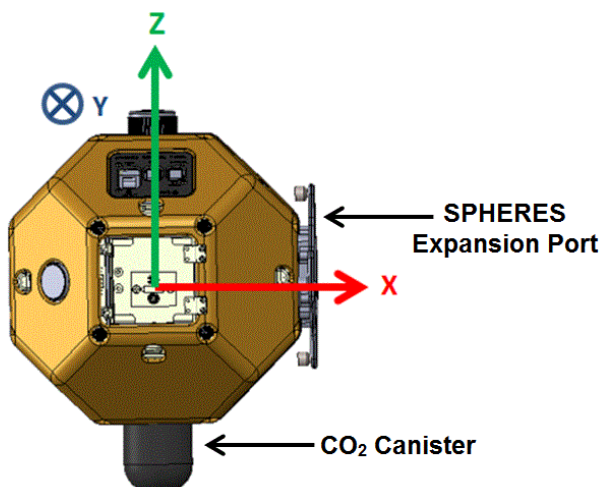


Figure 121: SPHERES Assembly

The VERTIGO Goggles subassembly is pictured in Figure 122, followed by the VERTIGO Avionics stack subassembly in Figure 123.

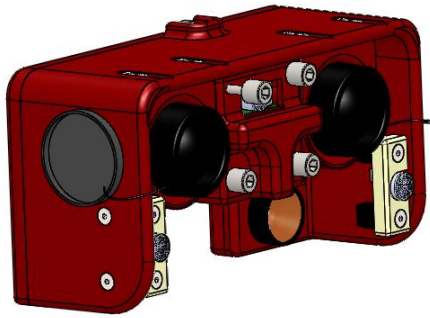


Figure 122: VERTIGO Goggles Subassembly

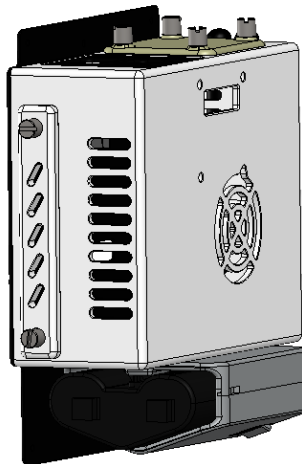


Figure 123: VERTIGO Avionics Stack Subassembly

The Halo subassembly pictured in Figure 124 is shown with SPHERES, Halo, and the VERTIGO Avionics Stack. The Halo structure is 43.4 cm wide (from HP5 to HPG) and 40.9 cm in height [3].

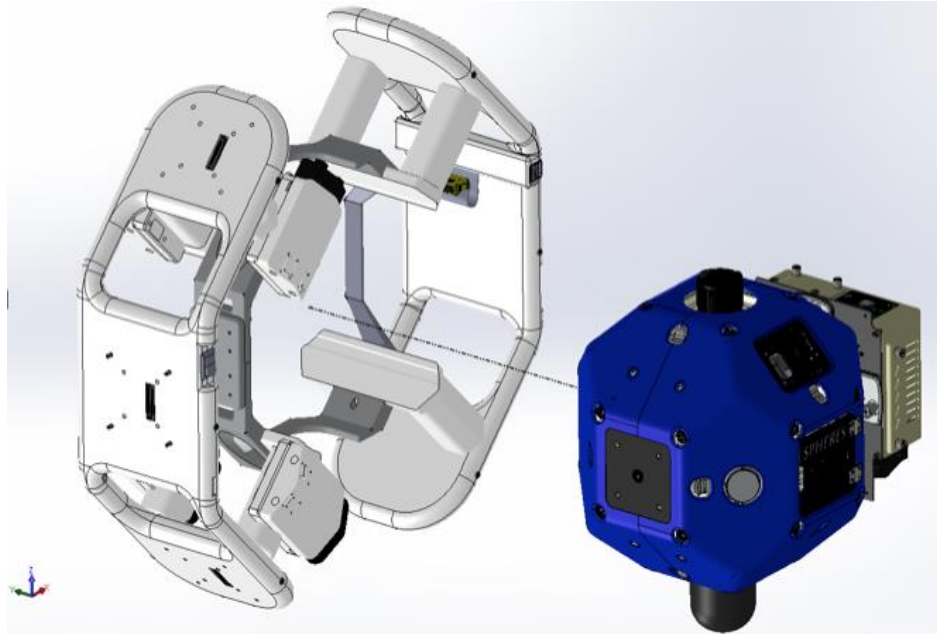


Figure 124: Halo Subassembly with SPHERES and VERTIGO Avionics Stack

14.3 INSPECT Sensor Components

14.3.1 Thermographic Camera

A summary of the Thermographic Camera is depicted below along with the mounting structure as discussed in Section 4.1.4.3.

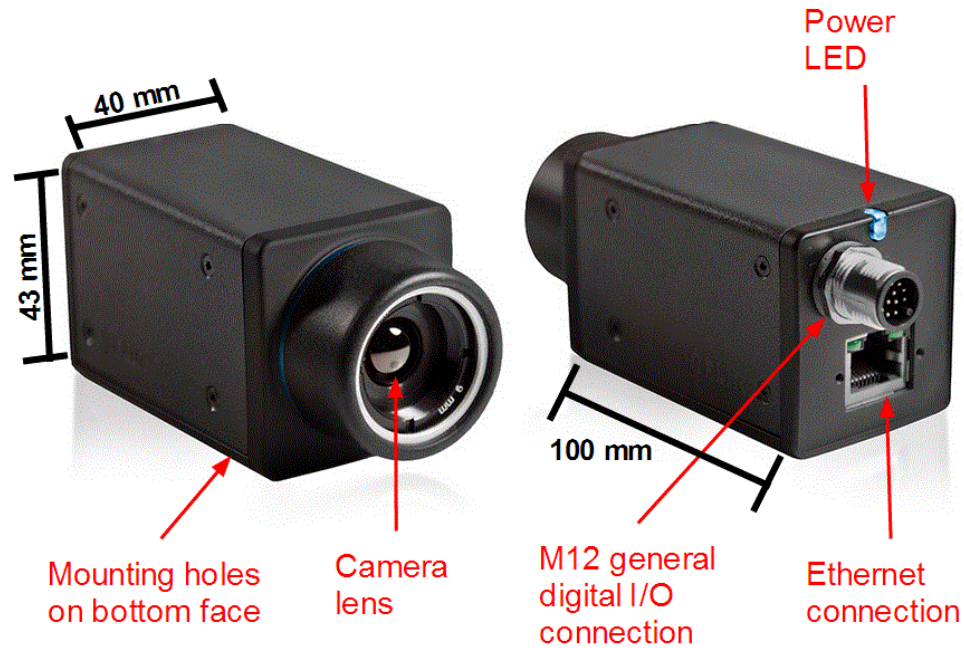


Figure 125: Thermographic Camera Summary

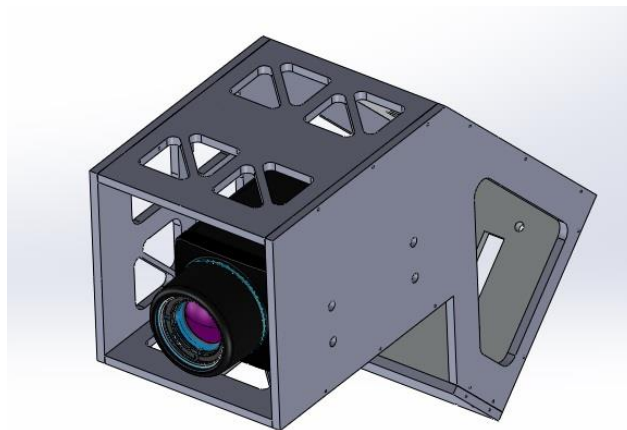


Figure 126: Thermographic Camera with Mount

14.3.2 Optical Rangefinder

A summary of the Optical Rangefinder is depicted below along with the mounting structure as discussed in Section 4.1.3.3.

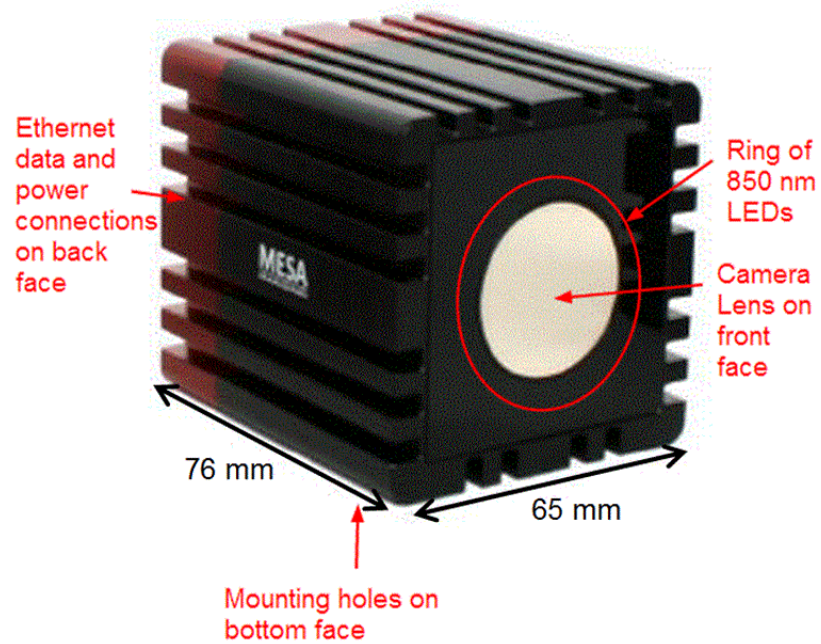


Figure 127: Optical Rangefinder Summary

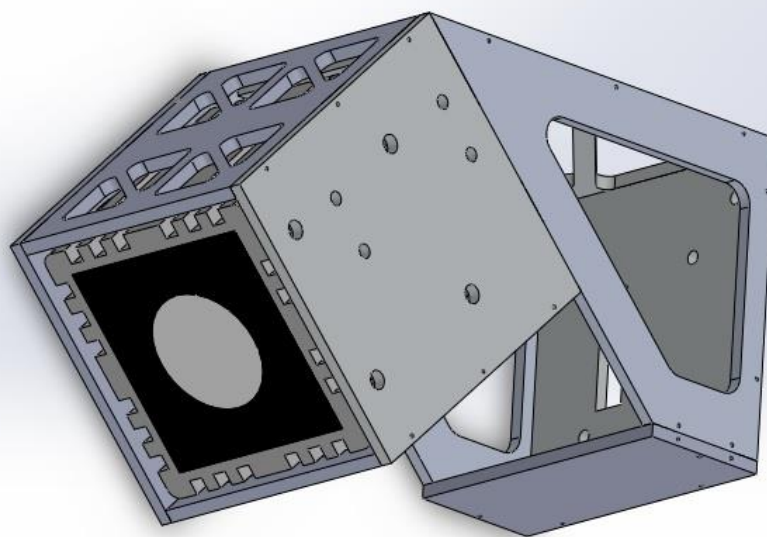


Figure 128: Optical Rangefinder with Mount

14.3.3 CMG Subassembly [4]

The mounting structure for the Honeybee CMG is detailed in Section 4.1.5.

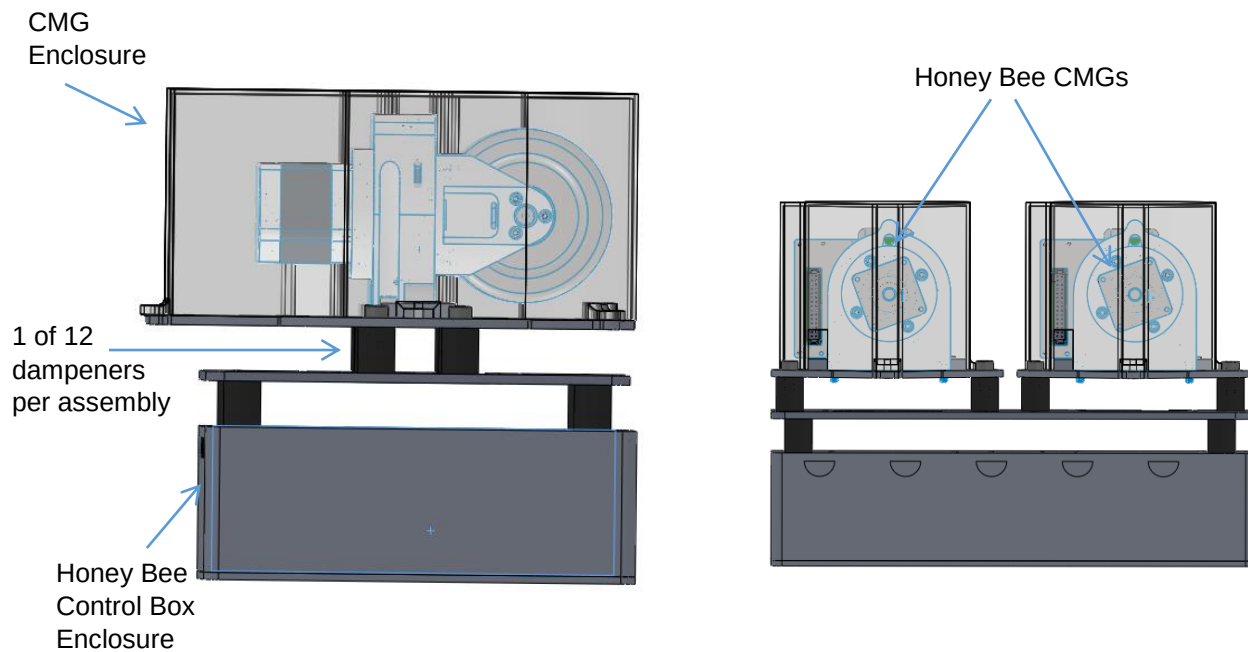


Figure 129: CMG Mounting Assembly Components (Side and Back Views)

The fully integrated CMG subsystem is represented in the box-90 control configuration without wiring in Figure 130 below.

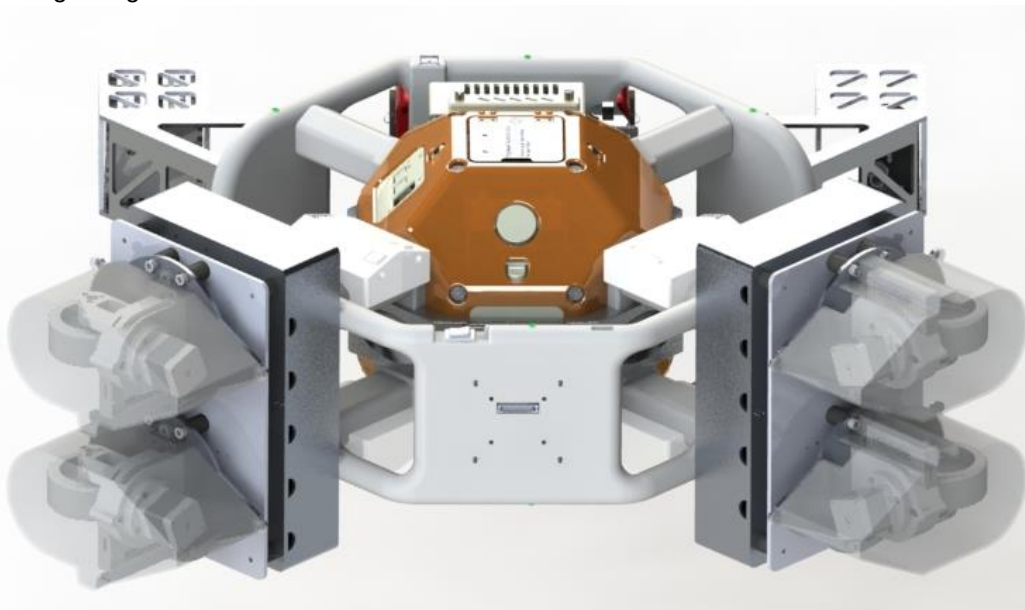


Figure 130: Integrated CMGs in Box-90 Control Configuration

15 Appendix F: Requirements Flow (JW)

15.1 Mission Requirements

Mission requirements state the overall goal of what the SPHERES INSPECT platform plans to achieve.

15.2 Constraining Requirements

Constraining requirements relate to other systems that INSPECT will have to integrate with. For proper integration INSPECT will have to be designed to meet the existing specifications of the following systems.

2. International Space Station
3. ISS and Lab safety
4. SPHERES
5. VERTIGO
6. Halo

15.3 Development Requirements

Development requirements outline how 16.83x INSPECT plans to achieve the mission requirements while under the constraints of the other systems.

15.3.1 SPHERES-X Requirements

SPHERES-X requirements are meant to show traceability to the eventual goal of EVA missions.

15.3.2 INSPECT Suite Requirements

INSPECT requirements flow from SPHERES-X requirements and place limitations on how our suite shall perform the traceable functions outlined in the SPHERES-X requirements.

It should be noted that not all SPHERES-X EVA requirements will be pursued by 16.83x INSPECT. Certain EVA requirements such as radiation hardening and the ability to survive extreme thermal gradients are not in scope for ground testing.

15.3.3 Sensing Requirements

Sensing requirements outline the specifications of the sensors for the INSPECT suite.

15.3.4 Control and Actuation Requirements

Control and actuation requirements define how SPHERES INSPECT will change the pose of the system through space. This includes overall system movement as well as controls required for proper sensing.

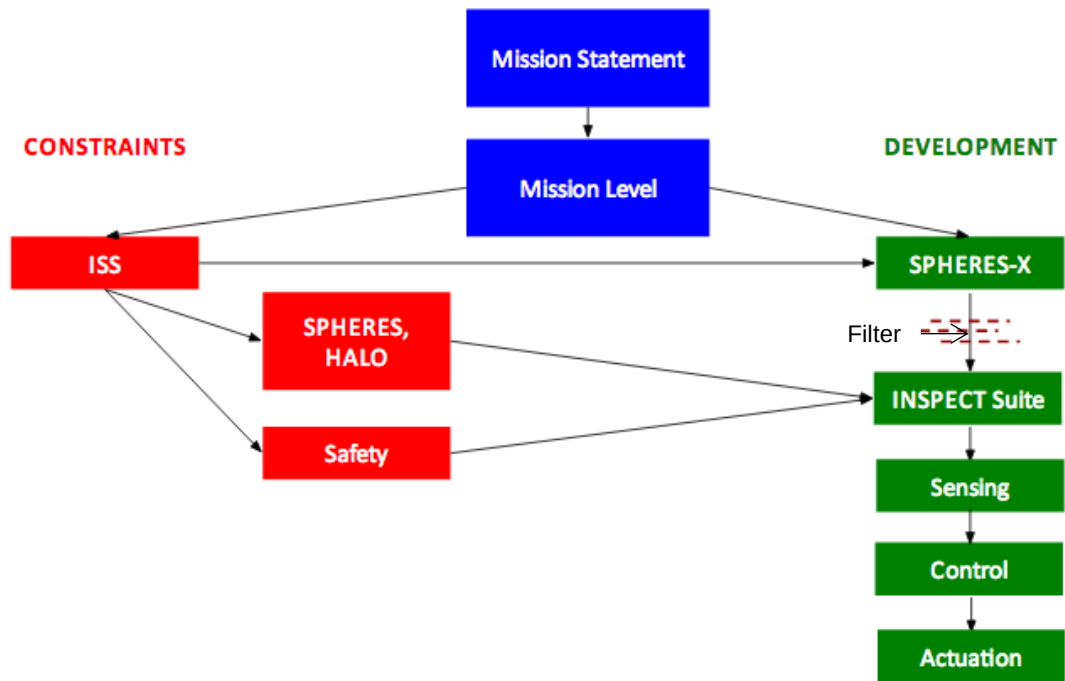


Figure 131: Graphical interpretation of requirements flow